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# 25 Hz SYSTEM LOAD MEASUREMENTS : HAMILTON GAGE TS

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Measurements were performed to characterize the load variations occurring on the 25 Hz system at Gage TS to assist in planning studies into future 25 Hz supply options. In addition, harmonic distortion measurements were conducted at Gage TS (25 Hz) and Beach TS (60 Hz) to aid in the development of detailed specifications for frequency conversion equipment planned for this area. Comparisons are made between the measured results and applicable standards for harmonic distortion limits.



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## 1.0 BACKGROUND

As part of the Southwestern Ontario transmission expansion plan, a single circuit 500 kV line is to be built between Nanticoke GS and the London area. The routing of this new line will require the removal of 25 Hz 115 kV circuit A8W between the Buchanan TS frequency changers and Allanburg TS. The only other ties to the 25 Hz system are a single frequency changer at Beck GS I and a 25 Hz interconnection to Niagara Mohawk. Once the Buchanan frequency changers have been removed from service (early to mid-1989) contingencies involving the Beck GS I frequency changer could result in isolated operation of the Niagara 25 Hz system.

Preliminary studies conducted by the System Planning Division (SPD) have revealed that isolated operation of the 25 Hz system could result in unacceptable frequency deviations due to rapid customer load variations occurring at Hamilton Gage TS. One solution to this problem, under active consideration, is the installation of static frequency converters at Hamilton Gage TS to provide an interconnection between the 13.8 kV 25 Hz system at Gage and the 115 kV 60 Hz system at Hamilton Beach TS [1]. The earliest anticipated in-service date for providing an interconnection at Hamilton Gage TS is late 1989. Therefore, there will be an extended period of time during which an increased possibility of isolated 25 Hz system operation will exist.

Based on the above, at the request of Transmission Stations Programs, a number of measurements were performed with the following objectives:

- monitor customer load variations at Hamilton Gage TS to provide input to detailed studies into frequency deviations during isolated 25 Hz system operation.
- perform harmonic measurements at Hamilton Gage TS and Beach TS to be used along with the load monitoring information in the production of a detailed specification for the planned static frequency changers.

### 1.1 Hamilton Gage TS

Figure 1 is a simplified single line diagram of the 25 Hz section of Hamilton Gage TS. The B-Q bus-tie breaker is normally operated open with a pair of transformers, T2 and T7 supplying the Q bus and a single transformer, T1, supplying the B bus. Eight dedicated feeders supply the two large industrial customers, Stelco and Dofasco. According to the System Planning Specification [1] the 15 minute peak load for all of the 25 Hz load at Gage TS is 50 MVA at close to unity power factor.

Feeders M1 and M7 supply the Stelco West (Bloom) Mill which is currently idle. No information was obtained regarding the future status of this load. Feeder M2 supplies the Stelco Cold Roll Mill and Feeders M4, M6 and M8 are connected to the largest single load at Gage TS, the Stelco East (Strip) Mill. The East Mill has customer interconnections to the West Mill (not shown) and the Cold Roll Mill. According to Operations Staff at Beach TS these interconnecting circuits are normally operated open-circuited. In addition, two small customer-owned 25 Hz generators (5 MVA and 6 MVA) are connected to the East Mill.

The Dofasco load is supplied by two feeders, with M3 supplying three arc furnaces and M5 feeding a small load consisting primarily of synchronous and induction motors. Reference [1] includes a detailed listing of the major customer equipment connected to the 25 Hz system at Hamilton Gage TS.

## 2.0 LOAD MONITORING : INSTRUMENTATION AND TEST RESULTS

The load monitoring tests were performed over a two week period commencing on November 15, 1987. The real and reactive power loads on feeders M2, M3, M4, M5 and M8 (M6 feeder load identical to M4) were monitored along with the B and Q bus voltages. Bus voltages were obtained from the T1 and T2 metering PTs and stepped down to a suitable voltage level using available autotransformers. Feeder currents were monitored using the protection CTs since metering CTs are not installed on the individual feeders at this location.

Table 1 lists the transducers and filters used in measuring each of the monitored quantities. The total power fed to the Stelco East (Strip) Mill was obtained by summing the outputs of the individual feeder WATT and VAR transducers; the load on the M4 and M6 feeders was found to be identical and therefore only one feeder was monitored and the output of its transducers was doubled. For quantities subject to rapid variations, the transducer outputs were also monitored with all filtering removed.

A Hewlett Packard 6940B scanning system with a twelve bit A/D converter was utilized to perform the load monitoring. Sixteen channels were scanned at a rate of 50 samples/second for four minute periods. The monitored quantities are listed in Table 2. Long term and overnight measurements were performed using a six channel direct-writing oscillograph. This recorder permitted identification of loading trends and selection of heavily loaded and rapidly varying conditions for closer examination.

The following load characteristics were identified from analysis of the collected data:

- maximum and minimum load levels
- power factor
- maximum loading rates
- cyclic load variations

The last two items are directly related to isolated system frequency control and governing. These results along with a number of plots of typical load and voltage variations are presented in the following sections for each of the monitored loads.

### 2.1 Test Results

#### 2.1.1 Stelco East (Strip) Mill - Feeders M4, M6 and M8

The largest single customer load at Gage TS is Stelco's East Mill which is supplied by three dedicated feeders M4, M6 and M8. From the customer equipment list provided in Reference [1] it is apparent that a major component of the Stelco load is large synchronous motors. In addition two customer-owned synchronous generators are connected to the East Mill. According to operating staff at Hamilton Beach TS, the two generators are normally operated to produce maximum output (combined rating of 11 MVA) and meet the load's reactive power requirements when the East Mill demand is at its peak.

The East Mill real power load tends to follow a regular pattern with the load cycling from no-load, up to a peak of 25 to 35 MW. This pattern is repeated every two to three minutes and the mill can operate in this mode for several hours at a time. Figures 2, 3 and 4(a) provide examples of the load variations encountered during the two week monitoring period (Note: plots are labelled as "M4" but actually correspond to total load on feeders M4, M6 and M8).

As can be seen in these figures numerous "step" load changes occur during each of the load cycles. The magnitude of these real load "step" changes vary, but are normally in the range of 5 to 13 MW. Figure 4(b) provides a close-up of several real and reactive power "step" changes occurring in Figure 4(a). Following each of the rapid load changes the load oscillates for one or two cycles at a frequency slightly above 1 Hz. A record showing one such oscillation in detail is plotted in Figure 5. Based on the observed frequency it is believed that these oscillations are the result of electro-mechanical swings of the numerous synchronous motors and the two customer-owned synchronous generators.

The leading edge of the "step" changes was measured without filtering directly from the output of the Hall-effect watt transducers; these transducers have a virtually instantaneous time response. The fastest rate-of-change of real power measured was 60 MW/s, corresponding to a 9 MW increase in 150 msec.

Of particular interest in determining the ability of existing governors to provide adequate frequency control under isolated conditions is the maximum rate-of-change of the entire block of East Mill load. During the test period a decrease of 26 MW within 9 seconds was the most rapid overall load decline encountered. For load modelling purposes a reasonable assumption would be that the load could be maneuvered between 0 and 35 MW within 10 seconds.

Examination of Figures 2, 3 and 4 indicates that the total reactive power supplied by feeders M4+M6+M8 is close to zero (power factor $\simeq$ 1) when the real power load increases towards 30 MW. As the load decreases the over-excited generators feed reactive power back into the system. With the mill's real power load reduced to zero, 6 to 7 MVAR of reactive power is injected into the Q bus resulting in bus voltage levels in excess of 14.1 kV.

### 2.1.2 Stelco Cold Roll Mill - Feeder M2

The remaining feeder on the Q bus, M2, is dedicated to the Stelco Cold Roll Mill. The load variations on this feeder are gradual when compared to the Stelco East Mill load. Figure 6 is an example of part of one cycle of the load variation. The load normally remains at its maximum level of 10 MW for anywhere between 1 to 10 minutes and then returns to the lower loading level. The loading and unloading rates are 0.8 MW/s and 1.5 MW/s respectively.

The maximum real power encountered on Feeder M2 during the test period was 13 MW. The reactive power normally remains close to zero and the power factor can be considered to be close to unity for analysis purposes. Variations in the reactive power and bus voltage seen in Figure 6 are due to load step changes of the Stelco East Mill load which is also fed from the Q bus. Comparison of Figure 6 with Figures 2, 3 and 4 confirms that the customer interconnection between the East Strip Mill and Cold Roll Mill is open circuited since reactive power changes for the two loads are in opposite directions (i.e. reactive power surpluses at the East Strip Mill flow onto the "Q" bus and then toward the Cold Roll Mill on feeder M2).

### 2.1.3 Dofasco Arc Furnaces - Feeder M3

Three separate arc furnaces are connected to feeder M3 with individual ratings of 7.5 MVA, 4.0 MVA and 1.2 MVA. No information was available during the course of the tests regarding which furnaces were operating at any given time, however, several distinct modes of operation were identified during the monitoring period.

Figures 7 through 9 provide examples of the load variations on Feeder M3 during periods when one or more of the furnaces was in a melting phase of operation. The real and reactive load (and consequently bus voltage) vary rapidly, with power spikes of up to 10 MWs and 10 MVARs and voltage spikes of up to 0.8 kV occurring on occasion. The width of these load spikes varies (compare Figure 7 with Figures 8 and 9) with high loads being maintained for one or more seconds at certain times.

The melting phase of operation characterized by the large load variations is normally only present for a few minutes at a time followed by periods in which the load is relatively constant. These periods of steady arc furnace load correspond to a refining mode of operation during which the metal is in a molten state and the arc remains relatively constant. Figure 10 shows a case where the melting phase of operation ends leaving a relatively constant furnace load of approximately 3 MW. In Figure 11 the furnace load is abruptly switched on and then off.

During the two week test period the largest varying peak real load observed on Feeder M3 was 15 MW with sustained loading occasionally reaching 9 MW. Due to the large customer transformers connecting the arc furnaces to the system, the power factor of the load is quite low. The measured power factor of the overall load on M3 varied between 0.8 and 0.9 depending on which furnaces are operating at any given time.

### 2.1.4 Dofasco - Feeder M5

The final active feeder, M5, supplies a small Dofasco load. The load level is normally 2 to 3 MW, at close to unity power factor. On occasion the load increases to slightly higher levels, however there is no particular pattern and the changes are gradual.

### 2.1.5 Station Load

Figures 12 and 13 provide representative records of load variations on all of the feeders at Gage TS, along with some totalized measurements; e.g. Q bus MWs and MVARs represents the total load supplied to Feeders M2, M4, M6 and M8 from transformers T2 and T7.

The final record, Figure 13, was captured while the station was operating with the B-Q bus tie breaker closed and transformer T7 removed from service. In this configuration the station's total real and reactive power load represents the combined loading on transformers T1 and T2.

## 2.2 Discussion

Clearly, the large Stelco East (Strip) Mill load will have the largest impact on regulation of the 25 Hz system frequency under isolated conditions. If necessary a "worst-case" scenario can be developed by assuming that all customer loads at Gage TS are increasing or decreasing at their maximum rates simultaneously. Such a scenario could provide an estimate of the maximum frequency deviation for comparison versus maximum permissible levels.

One method, currently under discussion, for reducing frequency deviations under isolated conditions, involves transmission of a load-anticipatory signal from the Stelco East Mill to the electro-hydraulic governor (EHG) of one of the 25 Hz units at Beck I GS. Given the irregular nature of the load variations at this plant, it seems unlikely that such a scheme could provide a reliable method of accelerating unit response and eliminating the 25 Hz system load/generation imbalances during operation of the Stelco East Mill.

Studies should be focused on whether adjustment of the new EHG control parameters may be utilized to minimize load imbalances and provide adequate frequency regulation for isolated operation. Consideration should also be given to alternative governor control schemes such as introducing a derivative input to the current arrangement. Simplified preliminary studies suggest that such an approach could improve the unit's response to rapid load changes.

## 3.0 HARMONIC DISTORTION MEASUREMENTS

Harmonic measurements were performed on November 25, 26 and 27, 1987 at Hamilton Gage TS and Hamilton Beach TS. The harmonic content of the following quantities was measured:

- Gage TS 25 Hz, 13.8 kV
  - feeder currents
  - transformer secondary currents
  - B and Q bus voltages
- Beach TS 60 Hz, 115 kV
  - circuits H5K and H6K currents
  - ring bus voltage

The measurements at Gage TS were performed for two different configurations: B and Q buses operated split (normal configuration with bus-tie breaker open) and B and Q buses tied together and fed by two transformers T1 and T2 respectively.

On the 25 Hz system an effort was made to take readings during a variety of different loading conditions. For selected measurements the frequency domain readings are cross-referenced to time domain plots showing the real and reactive power loading at the time of measurement (Figure 14 for Feeder M3 and Figure 15 for Feeder M4).

Previous harmonic distortion measurements were performed at Hamilton Gage TS on the 60 Hz 13.8 kV system at the request of Stelco. The results of these measurements are documented in Reference [2].

### 3.1 Instrumentation

Voltages for the harmonic measurements were obtained from the 13.8 kV metering PTs (120:1) and stepped down using 2.5:1 autotransformers followed by 30:1 isolation transformers. Although no specific information is available on the PTs used in these measurements, it is believed that their frequency response may be limited to 1 kHz [3].

Since individual metering of feeders is not available at Gage TS, currents were measured from the feeder circuit breaker protection CTs (all ratios equal to 1200:5 except feeder M2 with ratio 1600:5). The secondary currents were measured using a clamp-on CT, terminated to produce a 1 V/A output. The frequency response of the CTs is assumed to be reasonable up to 2.5 kHz.

A Hewlett Packard 3562A Dynamic Signal Analyzer was used to perform single-channel harmonic measurements on the various voltages and currents. For most measurements a 1.6 second window of sampled data was captured and stored allowing for examination of the waveform distortion in both the time and frequency domains.

Multi-channel monitoring of the current and voltage waveforms was also performed on-site using a Hathaway Digital Fault Recorder - GFR 1632. One or more phases of each of the feeder currents and the bus voltage were monitored simultaneously to allow for a rough visual assessment of the phase imbalance of the various loads.

3.2 Figures of Merit

One common figure of merit used to assess the harmonic distortion level is the Total Harmonic Distortion (THD), defined as:

$$THD = \frac{\left( \sum_{n=2}^{N} V_n^2 \right)^{1/2}}{V_{fund}} \times 100\%$$

where,

$V_{fund}$ = fundamental component of voltage

$V_n$ = nth harmonic voltage

n = harmonic number

The limits imposed on the THD by Ontario Hydro, for the Distribution Electricity System (DES) is 3% on a general feeder and 5% on a dedicated feeder [4]. Although there are no equivalent standards for the acceptable level of THD on the Bulk Electricity System (BES), recommended limits have been proposed [5,6]. The proposed limits on THD at voltage levels of 115 kV and above is 1.5%.

Normally the restriction on the harmonic content of power-line currents is based on limiting the noise induced on adjacent telephone circuits. To this end, the I•T product is computed by appropriately weighting and summing each harmonic current. Computation and use of the I•T product as a figure of merit is only applicable where exposures exist between above ground power circuits and above ground telephone circuits.

All feeders exiting Gage TS are cables. Based on available information there are no overhead sections of these circuits and therefore no exposures to overhead telephone lines In addition, the two 115 kV circuits, Q7PG and Q8TG, are also cables. These circuits are to be re-terminated on the H5K and H6K positions in the 115 kV Beach TS switchyard and used to connect the 60 Hz system to the proposed static converter. Based on the above, I•T products were not computed for the measured current harmonics and I•T levels should probably not be considered as a design limitation in converter selection at this site.

One figure of merit which may be relevant in relation to the current harmonics at Gage TS is the harmonic contribution to the total RMS current since this relates to increased heating effects in equipment and cables. The total RMS current may be computed indirectly by using the THD as,

$$I_{RMS} = ( 1 + THD^2 )^{1/2}$$

where THD and $I_{RMS}$ are both expressed in per-unit of the measured fundamental current.

## 3.3 Results

Harmonic spectra are plotted up to 1 kHz and markers are included which indicate the exact location of each harmonic up to the twenty-first order. A portion of the captured time record used in calculating the frequency components is displayed along with each plotted spectrum. THD values are computed directly by the 3562A Dynamic Signal Analyzer and are based on the first 21 harmonics.

In most cases the THD values and the plotted harmonic spectra are mean values based on nine frequency-domain averages with 50% overlap, using a Flat Top window and a 2.5 kHz frequency span. For certain conditions the frequency spectrum and computed THD are based on the peak values for the captured record of time domain data. Given the rapid load variations occurring on certain feeders at Gage TS, consecutive measurements performed on the three phases of each voltage or current may represent markedly different loading conditions. Therefore, readings are tabulated along with measurement times, load levels and other pertinent information.

### 3.3.1 Gage TS 13.8kV Bus Voltages

THD values for the B and Q bus voltages are given in Table 3 for operation with the bus-tie breaker both open and closed. Harmonic spectra for three selected measurements are plotted in Figures 16, 17 and 18.

The mean THD for all measurements, performed with both configurations, was well within the applicable 3% limit. On the Q bus there was relatively little variation in the harmonic content of the voltage for different measurements. The voltage waveshape distortion and harmonic content variations on the B bus were more significant due to the rapid changes in the Dofasco arc furnace load (Feeder M3). To determine the extent of these variations the peak-hold capability of the signal analyzer was utilized. In this mode the largest component of each frequency spectral line is stored for the nine Fourier Transforms performed on each time record. THDs calculated using the maximum fundamental and harmonic components were higher, ranging between 2.4% and 3.6%, than the mean THDs computed from the same time records (Table 3 - B bus entries). Examination of individual frequency response measurements also revealed that the B bus voltage THD occasionally went above 3%. Reference [4] does not provide specific guidelines to be followed when analyzing fluctuating loads.

Interconnection of the two 13.8 kV buses resulted in a reduction in the amplitude of each individual harmonic and the overall THD.

### 3.3.2 Gage TS 13.8 kV Feeder Currents

Tables 4 through 7 list THD and $I_{RMS}$ measurements for feeders M2, M3, M4 and M5.

#### 3.3.2.1 Stelco Cold Roll Mill - Feeder M2

The percentage THD of the Cold Roll Mill feeder current varies widely with load level. This is in part due to the fact that the level of the dominant seventh harmonic component remains constant at around 9 A RMS irrespective of the magnitude of the fundamental current. Figures 19 and 20 provide two examples of the feeder current distortion for two different load levels; the fundamental current is equal to 123 A RMS for Figure 19 and 462 A RMS for Figure 20. The presence of a relatively constant seventh order harmonic component, along with the

presence of a significant 11th order component, suggests that there may be a small rectifier load in the Cold Roll Mill. From Table 4 it can be seen that the harmonic contribution to the total RMS current is negligible at high loads.

3.3.2.2 Dofasco Arc Furnaces - Feeder M3

The non-linear voltage-current characteristics of the arc furnace load introduces harmonics of virtually every order [7]. Because of the sudden changes in the magnitude of the fundamental component of the load current and the associated harmonics, a very wide range of THD levels were encountered during the measurements. For this reason both averaged and peak-hold values for the THD are listed in Table 5. A number of the measurements contained in Table 5 are cross-referenced to Figure 14 to provide an indication of the load's activity during the harmonic measurements.

The current waveform distortion and harmonic content are significantly worse during the active melting phase of operation. Figure 21 provides an example of a portion of the time-domain record and frequency spectrum for a measurement conducted during load conditions characteristic of such a phase of operation. Because of the highly distorted nature of the current during this phase of operation energy is spread throughout the frequency spectrum. The odd current harmonic components have slightly greater magnitudes than the even and non-harmonic components in the spectrum, particularly for the lower frequencies.

Figure 22 is an example of the frequency spectrum during a period of relatively constant load such as during a refining phase of operation. Under these conditions the relative level of the harmonics remains somewhat more constant between measurements conducted at different times. From Figure 22 it can be seen that the level of non-harmonic components appearing in the frequency spectrum is significantly reduced during this phase of operation as all low-order odd harmonic components are now clearly visible.

Maximum levels of the largest current harmonic component, the third, measured during the various load conditions varied between 3 and 20%.

Figures 23 and 24 are two examples of the phase imbalance and waveform distortion in the arc furnace load currents during different load conditions. The level of both the fundamental and harmonic components was found to vary markedly between phases. This imbalance condition was present even during periods when the load was relatively constant.

3.3.2.3 Stelco East (Strip) Mill - Feeder M4

Table 6 provides THD values for measurements conducted on one of the paralleled feeders, M4, supplying Stelco's East Mill. A number of the tabulated values are cross-referenced to Figure 15, providing a rough indication of the load profile during these measurements. As discussed in the load measurement section, the East Mill load is comprised mainly of large synchronous motors and motor-generator sets. As expected the harmonic content of the East Mill load current was quite low for all of the measurements conducted at a variety of load levels.

Information provided in Reference 1 indicates that a rectifier, rated at 300 kVA, is connected to the SP substation which is fed at a lower voltage level from Stelco's East Mill supply. The measurements shown in Figures 25 and 26 indicate the presence of small levels of the characteristic harmonics of order $6n\pm1$ (n is any integer) associated with a six-pulse rectifier operation.

As was the case with the other loads the contribution of the harmonic currents to the total RMS current was virtually negligible for all the measurements.

3.3.2.4 Dofasco - Feeder M5

Table 7 lists the results of a number of the harmonic distortion measurements performed on the Dofasco load. The fundamental component of the load current on Feeder M5 is normally quite small, at around 100 A RMS. Therefore, although the THD values listed in Table 7 vary between 5% and 8%, the actual magnitude of the harmonic currents involved is very small.

Figures 27 and 28 are two examples of the frequency spectra measured on the M5 Feeder. These spectra are somewhat similar to those measured for the arc furnace load which is also connected to the B bus. Examination of the phase spectra for some of these measurements was inconclusive and did not clarify whether the M5 load was the source of these harmonics or whether harmonic currents from the arc furnace load (feeder M3) were flowing onto Feeder M5 via the B bus.

3.3.3 Gage TS 13.8 kV - Transformer Secondary Currents

For reference purposes, Tables 8 and 9 list a number of THD values for measurements performed on the T1, T2 and T7 transformer secondary currents. The harmonic content of the T1 secondary currents is largely dependent on the arc furnace load and therefore varies widely depending on the furnaces phase of operation. The percentage harmonic distortion of both the T1 and T2 secondary currents were relatively small for measurements performed with the bus-tie breaker closed.

3.3.4 Harmonic Impedance Measurements - 25 Hz System

A simple attempt was made to determine the harmonic (load or system) impedance on the two 13.8 kV buses at Gage TS. Transfer functions of 13.8 kV bus voltage/feeder current were measured for each of the feeders at Gage TS. Since no attempt was made to isolate the individual harmonic producing loads from each other, the measured results were relatively poor. Also, since measurements were performed on the 13.8 kV bus, and not at the point of common coupling, the impedance of the feeder cables are included as part of the measured load impedances.

The measurements were performed directly using the 3562A Dynamic Signal Analyzer with the same settings as used in the other harmonic measurements. For each measurement the coherence function was automatically calculated and stored along with the impedance data. The coherence provides a measure of the relationship between the output harmonic voltage, and the input harmonic current. A coherence of unity indicates that a measured harmonic voltage was due entirely to the measured harmonic current input.

Tables 10 and 11 list the impedance results for each of the harmonics for which the measured coherence was high ( > 0.9 ). To interpret the results contained in these tables, the following conventions should be followed [8]. When the impedance transfer function angle falls between -90° and +90°, power flow is towards the load and the measured value represents the load impedance (0° to 90° inductive, 0° to -90° capacitive). For phase angles between +90° and 180° or -90° and -180° power flow is from the load onto the system and the measured value represents the system impedance at the point of measurement (-90° to -180° inductive, 90° to 180° capacitive). Examining the results contained in the tables, it can be seen that for each of the feeders fundamental power flow is towards the load as expected. The fundamental frequency phase is the power factor angle at the time of measurement.

Producing a complete set of impedance measurements proved to be difficult and the number of harmonics registering high coherence values was quite small. There are a number of factors which may have contributed to this result. First, the loads at Gage TS produce relatively small levels of steady harmonic currents. Second, since each bus feeds a pair of loads it is difficult to establish the one-to-one harmonic voltage-current relationship necessary to accurately determine the impedance of the system or a given load at a single point. Finally, for the arc furnaces the coherence of the impedance measurement is inherently low due to the highly non-linear nature of the load.

If, for detailed study purposes, an accurate measurement of system impedance is required at Gage TS, measurements could be performed under controlled conditions, either utilizing the existing harmonic current injection from each load or introducing a separate harmonic source.

### 3.3.5 Beach TS 115 kV - Voltage and Current Harmonic Measurements

To provide a basis for future comparisons, measurements of the Beach TS 115 kV ring bus voltage and selected currents were conducted. Circuits H5K and H6K were chosen for the current measurements. As part of the SPD specification [1], 60 Hz circuits Q7PG and Q8TG are to be connected to the proposed frequency changers at Gage TS and re-terminated in the Beach TS switchyard in the same positions as circuits H5K and H6K.

Table 12 lists THDs for both voltage and current measurements. Measured 115 kV bus voltage distortion levels were below the 1.5% recommended limits [5,6].

## 3.4 Discussion

Voltage THD levels on the Gage TS 25 Hz 13.8 kV bus were within the 3% limit imposed on general feeder supplies. The voltage distortion levels on the 115 kV bus at Beach TS were also within the proposed limits of 1.5%. The percentage distortion levels on the feeder currents varied widely, particularly for the arc furnace loads supplied by feeder M3. As expected, the percentage distortion levels for the loads consisting primarily of synchronous and induction machines (Stelco Mills supplied by feeders M2, M4, M6 and M8) were quite low. The contribution of the harmonic currents to the total RMS current was negligible for all the measurements conducted on the feeders supplying steady loads (i.e. excluding feeder M3).

## 4.0 CONCLUSIONS

- Results have been provided which can be used to study future supply options for the Niagara 25 Hz system.

- Digital simulations are required to accurately assess the impact of the rapidly varying load at Gage TS on the 25 Hz system under isolated conditions. A "worst-case" scenario can be developed in which each load varies at its maximum loading/unloading rate simultaneously. For modelling purposes it may be assumed that the largest single load, the Stelco East (Strip) Mill, can vary between 0 and 35 MW within 10 seconds.

- Measured voltage harmonic distortion levels at Gage TS and Beach TS were within acceptable limits. If static frequency converters are installed at Gage TS, future measurements could be compared with the current results to assess the increase in harmonic distortion levels.


### 4.1 Acknowledgements

I wish to thank Mr. Paul Vejvalka, Mr. Wendel Ripley and the other P&C staff at Beach TS for their help in instrumenting and performing these tests.


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7. J. Arrillaga, D.A. Bradley, P.S. Bodger, "Power System Harmonics", John Wiley & Sons, 1985.

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TABLE 1

GAGE TS LOAD MONITORING - TRANSDUCERS AND FILTERS

| QUANTITY | | TRANSDUCER(S) | OUTPUT | FILTERING |
|---|---|---|---|---|
| Q and B BUS VOLTAGE | | RMS VOLTAGE TRANSDUCER | VARIABLE | 10 Hz LOW PASS[1] |
| M2 FEEDER | P | OSI WATT TRANSDUCER[2] | 0.1 mV/W | 10 Hz LOW PASS |
| | Q | PHASE SHIFTER PLUS OSI WATT TRANSDUCER | 0.1 mV/VAR | 10 Hz LOW PASS |
| M3 FEEDER | P | OSI WATT TRANSDUCER | 0.1 mV/W | 10 Hz LOW PASS |
| | Q | PHASE SHIFTER PLUS HALL WATT TRANSDUCER[3] | 0.2 mV/VAR | 10 Hz LOW PASS |
| M4 FEEDER | P | OSI WATT TRANSDUCER | 0.1 mV/W | 30 Hz LOW PASS[1] |
| | Q | PHASE SHIFTER PLUS HALL WATT TRANSDUCER | 0.2 mV/W | 10 Hz LOW PASS |
| M5 FEEDER | P | OSI WATT TRANSDUCER | 0.1 mV/W | 30 Hz LOW PASS |
| | Q | PHASE SHIFTER PLUS HALL WATT TRANSDUCER | 0.2 mV/W | 10 Hz LOW PASS |
| M6 FEEDER | P | NOT MONITORED - IDENTICAL TO M4 FEEDER | | |
| | Q | | | |
| M8 FEEDER | P | OSI WATT TRANSDUCER | 0.1 mV/W | 30 Hz LOW PASS |
| | Q | PHASE SHIFTER PLUS HALL WATT TRANSDUCER | 0.2 mV/W | 10 Hz LOW PASS |

Notes: (1) Filters used were 10 Hz and 30 Hz Active Bessel Filters (6 pole)

(2) OSI = Ohio Semitronics Inc., Hall Effect Watt Transducer, PC5-4

(3) HALL = Custom Hall Effect Watt Transducer

TABLE 2 - GAGE TS (MONITORED QUANTITIES)

| CHANNEL # | QUANTITY | RANGE[1] |
|---|---|---|
| 1 | STELCO COLD ROLL MILL M2 (MW) | ± 20 MW |
| 2 | STELCO COLD ROLL MILL M2 (MVAR) | ± 4 MVAR |
| 3 | DOFASCO ARC FURNACES M3 (MW) | ± 18 MW |
| 4 | DOFASCO ARC FURNACES M3 (MVAR) | ± 9 MVAR |
| 5 | STELCO EAST (STRIP) MILL 2 x M4 (MW) + M8 (MW) | ± 36 MW |
| 6 | STELCO EAST (STRIP) MILL 2 x M4 (MVAR) + M8 (MVAR) | ± 18 MVAR |
| 7 | DOFASCO M5 (MW) | ± 8 MW |
| 8 | DOFASCO M5 (MW) | ± 1 MVAR |
| 9 | Q BUS (kV) | ± 5% (13.8 kV base) Offset 14.2 kV |
| 10 | B BUS (kV) | ± 10% (13.8 kV base) Offset 13.8 kV |
| 11 | Q BUS TOTAL (MW) M2 (MW) + 2 x M4 (MW) + M8 (MW) | ± 80 MW |
| 12 | Q BUS TOTAL (MVAR) M2 (MVAR) + 2 x M4 (MVAR) + M8 (MVAR) | ± 20 MVAR |
| 13 | B BUS TOTAL (MW) M3 (MW) + M5 (MW) | ± 40 MW |
| 14 | B BUS TOTAL (MVAR) M3 (MVAR) + M5 (MVAR) | ± 20 MVAR |
| 15 | STATION TOTAL (MW) B BUS TOTAL (MW) + Q BUS TOTAL (MW) | ± 80 MW |
| 16 | STATION TOTAL (MVAR) B BUS TOTAL (MVAR) + Q BUS TOTAL (MVAR) | ± 20 MVAR |

(1) Ranges and offsets selected based on observed load variations to maximize resolution of measurements.

TABLE 3

GAGE TS VOLTAGE HARMONICS

| DATE | TIME | QUANTITY | %THD(MEAN) R-W | W-B | B-R | COMMENTS |
|---|---|---|---|---|---|---|
| Nov 25 | 14:05 | B Bus | 2.4 | 2.2 | 2.4 | Bus split. Refer to Figure 14, points D, E and F for load levels on arc furnace during measurement. Frequency spectrum for the R-W Ø measurement is plotted in Figure 16. |
| Nov 25 | 14:24 | B Bus | 2.5 | 2.6 | 1.8 | Bus split |
| Nov 26 | 09:32 | Q Bus | 1.1 | 0.9 | 1.4 | Bus split. Refer to Figure 15, points D E & F for load levels on rolling mill during measurement. Frequency spectrum for the B-R Ø measurement is plotted in Figure 17. |
| Nov 26 | 10:35 | Q Bus | 1.2 | 1.0 | 1.3 | Bus split. |
| Nov 27 | 14:20 | Buses Tied | 0.9 | 1.1 | 1.4 | Bus-tie breaker closed. Refer to Figure 13(a) and (b) for the load profile during the six voltage harmonic measurements. Frequency spectrum for the W-B Ø measurement is plotted in Figure 18. |
| Nov 27 | 14:22 | Buses Tied | 1.4 | 1.1 | 1.1 | |

TABLE 4

STELCO COLD ROLL MILL (FEEDER M2) HARMONICS

| DATE | TIME | PHASE | THD (%) | $I_{fund}$ (A RMS) | $I_{RMS}$ (pu $I_{fund}$) | COMMENTS |
|---|---|---|---|---|---|---|
| Nov 25 | 11:19 | RØ | 2.5 | 434 | 1.000 | Stelco Hot Srip Mill load low. |
| | 11:20 | WØ | 10.7 | 123 | 1.006 | Bus-tie breaker open. Refer to Figure |
| | 11:21 | BØ | 8.6 | 125 | 1.004 | 19 for plot of WØ measurement spectrum. |
| | 13:38 | RØ | 6.9 | 138 | 1.002 | Stelco Hot Strip Mill load high |
| | 13:38 | WØ | 9.5 | 123 | 1.005 | Bus-tie breaker open. |
| | 13:39 | BØ | 7.5 | 136 | 1.003 | |
| | 11:24 | RØ | 2.6 | 467 | 1.000 | Stelco Hot Strip Mill load low. |
| | 11:24 | WØ | 3.2 | 454 | 1.001 | Bus-tie breaker open. |
| | 11:24 | BØ | 2.9 | 456 | 1.000 | |
| | 11:41 | RØ | 2.6 | 462 | 1.000 | Stelco Hot Strip Mill load high |
| | 11:42 | WØ | 3.0 | 456 | 1.000 | Bus-tie breaker open.Refer to Figure |
| | 11:42 | BØ | 2.8 | 462 | 1.000 | 20 for plot of RØ measurement spectrum. |

TABLE 5

DOFASCO ARC FURNACE (FEEDER M3) HARMONICS

| DATE | TIME | PHASE | THD(Mean) (1) (%) | THD(Max) (2) (%) | $I_{Fund}$(Max) (3) (A RMS) | COMMENTS |
|---|---|---|---|---|---|---|
| Nov 25 | 14:04 | RØ | 9.0 | 12.4 | 301 | Bus-tie breaker open. Refer to Figure 14, points A, B and C for load levels during measurement. Refer to Figure 21 for plot of BØ spectrum. |
| | 14:05 | WØ | 11.6 | 15.6 | 240 | |
| | 14:05 | BØ | 24.4 | 25.7 | 181 | |
| | 14:22 | RØ | 6.0 | 7.5 | 269 | |
| | 14:23 | WØ | 12.0 | 14.2 | 304 | Refer to Figure 22 for plot of WØ spectrum. |
| | 14:24 | BØ | 9.4 | 12.1 | 493 | |
| | 14:38 | RØ | 13.6 | 16.5 | 284 | |
| | 14:38 | WØ | 11.9 | 12.0 | 626 | |
| | 14:39 | BØ | 12.3 | 15.8 | 390 | |

Notes:
(1) THD calculation based on average values of frequency components for nine averages of the time record.
(2) THD calculation based on maximum value of fundamental and harmonics for each time record.
(3) Maximum RMS value of fundamental current in each time record.

TABLE 6

STELCO EAST STRIP MILL (FEEDERS M4, M6 AND M8) HARMONICS[1]

| DATE | TIME | PHASE | THD (%) | $I_{fund}$[2] (A RMS) | $I_{RMS}$ (pu $I_{fund}$) | COMMENTS |
|---|---|---|---|---|---|---|
| Nov 26 | 09:31 | RØ | 3.1 | 76 | 1.001 | Bus-tie breaker open. Stelco Cold Roll Mill load high. Refer to Figure 15, points A, B & C for load levels during measurement. Refer to Figure 25 for BØ measurement spectrum. |
| | 09:31 | WØ | 3.0 | 144 | 1.001 | |
| | 09:32 | BØ | 3.6 | 156 | 1.001 | |
| | 10:33 | RØ | 1.5 | 317 | 1.000 | Refer to Figure 26 for RØ measurement spectrum. |
| | 10:33 | WØ | 2.4 | 188 | 1.000 | |
| | 10:34 | BØ | 3.0 | 140 | 1.001 | |

Notes:

(1) Harmonic measurements performed on feeder M4 only.

(2) $I_{fund}$ measured on Feeder M4 only.

TABLE 7

DOFASCO (FEEDER M5) HARMONICS

| DATE | TIME | PHASE | THD (%) | $I_{fund}$ (A RMS) | $I_{RMS}$ (pu $I_{fund}$) | COMMENTS |
|---|---|---|---|---|---|---|
| Nov 26 | 09:51 | RØ | 6.6 | 104 | 1.004 | Bus-tie breaker open. Dofasco Arc-furnace load operating. Refer to Figure 27 for plot of RØ spectrum. |
| | 09:51 | WØ | 7.6 | 94 | 1.001 | |
| | 09:52 | BØ | 7.0 | 101 | 1.004 | |
| | 09:57 | RØ | 5.9 | 98 | 1.002 | Refer to Figure 28 for plot of WØ spectrum. |
| | 09:57 | WØ | 5.4 | 97 | 1.002 | |
| | 09:58 | BØ | 7.3 | 92 | 1.003 | |

TABLE 8

GAGE TS TRANSFORMER T1 HARMONICS

| DATE | TIME | PHASE | THD (%) | $I_{Fund}$ (A RMS) | COMMENTS |
|---|---|---|---|---|---|
| Nov 26 | 11:37 | RØ | 5.2 | 403 | Bus-tie breaker open. Dofasco Arc-furnace load varying rapidly. |
| | 11:38 | WØ | 5.0 | 336 | |
| | 11:38 | BØ | 12.3 | 326 | |
| | 11:38 | RØ | 6.1 | 413 | |
| | 11:38 | WØ | 4.7 | 314 | |
| | 11:39 | BØ | 7.3 | 381 | |
| | 11:43 | N | 9.5 | 0.4 | |
| Nov 27 | 14:09 | RØ | 1.3 | 736 | Bus-tie breaker closed. Dofasco Arc-furnace load active (melting phase). Stelco Cold Roll Mill load = 8 MW. Stelco Hot Strip Mill load varying rapidly. |
| | 14:09 | WØ | 2.2 | 406 | |
| | 14:10 | BØ | 2.4 | 365 | |
| | 14:10 | RØ | 2.3 | 368 | |
| | 14:11 | WØ | 1.4 | 634 | |
| | 14:11 | BØ | 1.6 | 650 | |
| | 14:11 | N | 7.9 | 1.1 | |

TABLE 9

GAGE TS TRANSFORMERS T2 & T7 HARMONICS

| DATE | TIME | PHASE | THD (%) | $I_{Fund}$ (A RMS) | COMMENTS |
|---|---|---|---|---|---|
| Nov 26 | 11:58 | T2-RØ | 3.6 | 266 | Bus-tie breaker open. |
| | 11:58 | T2-WØ | 2.6 | 390 | Stelco Cold Roll Mill load = 8 MW |
| | 11:59 | T2-BØ | 1.7 | 509 | Stelco Hot Strip Mill load varying rapidly |
| | 12:00 | T2-N | 5.8 | 1.0 | |
| | 12:08 | T7-RØ | 1.9 | 576 | Bus-tie breaker open. |
| | 12:08 | T7-WØ | 2.3 | 406 | Stelco Cold Roll Mill load = 2 MW |
| | 12:09 | T7-BØ | 2.1 | 419 | Stelco Hot Strip Mill load varying rapidly |
| | 12:11 | T7-N | 6.0 | 1.5 | |
| Nov 27 | 14:12 | T2-RØ | 2.0 | 470 | Bus-tie breaker closed. |
| | 14:12 | T2-WØ | 1.9 | 320 | Dofasco Arc-furnace load varying rapidly |
| | 14:13 | T2-BØ | 2.0 | 374 | (melting phase). Stelco Cold Roll Mill |
| | 14:14 | T2-RØ | 1.3 | 682 | load varying rapidly. |
| | 14:15 | T2-BØ | 1.0 | 650 | |
| | 14:16 | T2-WØ | 1.4 | 608 | |
| | 14:19 | T2-N | 5.7 | 0.8 | |

TABLE 10

HARMONIC IMPEDANCE MEASUREMENTS - GAGE TS Q BUS

| HARMONIC NUMBER | FREQUENCY (Hz) | M2 IMPEDANCE MAGNITUDE[1] AND PHASE | | | M4[2] IMPEDANCE MAGNITUDE AND PHASE | | |
|---|---|---|---|---|---|---|---|
| | | RØ | WØ | BØ | RØ | WØ | BØ |
| 1 | 25 | 11.3 ∠0° | 12.7 ∠-2° | 11.5 ∠-2° | 13.7 ∠-10° | 13.5 ∠-9° | 18.7 ∠-18° |
| 3 | 75 | 26.0 ∠104° | 3.6 ∠164° | 18.0 ∠22° | 20.0 ∠67° | 8.9 ∠150° | 42.4 ∠-133° |
| 5 | 125 | 6.0 ∠0° | 6.7 ∠17° | 6.3 ∠-19° | 5.5 ∠0° | 4.8 ∠-8° | - |
| 7 | 175 | 0.5 ∠23° | 1.0 ∠23° | 0.7 ∠18° | 4.1 ∠-175° | 7.3 ∠148° | - |
| 9 | 225 | 4.1 ∠115° | - | - | 17.3 ∠73° | - | 44.7 ∠82° |
| 11 | 275 | 8.4 ∠-5° | 7.9 ∠9° | 8.9 ∠14° | 17.1 ∠25° | 18.7 ∠24° | 18.5 ∠42° |
| 13 | 325 | 2.7 ∠31° | - | - | 8.0 ∠109° | 8.9 ∠87° | - |
| 15 | 375 | - | - | - | - | - | - |
| 17 | 425 | 2.7 ∠-97° | - | - | - | 15.3 ∠169° | - |
| 19 | 475 | 6.8 ∠166° | - | - | - | - | - |
| 21 | 525 | - | - | - | - | - | - |
| 23 | 575 | - | - | - | - | - | - |
| 25 | 625 | 11.3 ∠72° | 7.9 ∠65° | 10.8 ∠79° | 6.4 ∠-104° | 8.2 ∠-110° | 9.8 ∠-103° |
| 27 | 675 | - | - | - | - | - | - |
| 29 | 725 | 11.2 ∠77° | 12.1 ∠83° | 12.7 ∠73° | 15.7 ∠-158° | 12.3 ∠-166° | - |
| 31 | 775 | 13.3 ∠102° | 12.0 ∠114° | 17.1 ∠103° | - | - | - |
| 33 | 825 | - | - | - | - | - | - |
| 35 | 875 | 16.9 ∠30° | 12.3 ∠25° | 12.8 ∠39° | - | - | - |
| 37 | 925 | - | - | - | - | - | - |
| 39 | 975 | - | - | - | - | - | - |
| 41 | 1025 | 7.4 ∠-159° | 6.3 ∠-161° | 7.0 ∠-160° | - | 105.3 ∠20° | - |
| 43 | 1075 | 5.1 ∠-96° | 6.2 ∠-93° | 5.8 ∠-100° | - | 87.5 ∠59° | - |

Notes:

(1) Magnitudes expressed in per unit on 13.8 kV 100 MVA base.

(2) Measurements performed on M4 feeder alone.

TABLE 11

HARMONIC IMPEDANCE MEASUREMENTS - GAGE TS B BUS

| HARMONIC NUMBER | FREQUENCY (Hz) | M3 IMPEDANCE MAGNITUDE[1] AND PHASE | | | M5 IMPEDANCE MAGNITUDE AND PHASE | | |
|---|---|---|---|---|---|---|---|
| | | RØ | WØ | BØ[2] | RØ | WØ | BØ |
| 1 | 25 | 28.9 ∠9° | 21.9 ∠13.4° | - | 45.4 ∠11.8° | 45.6 ∠2° | 39.9 ∠8° |
| 3 | 75 | - | - | - | - | 7.5 ∠39° | - |
| 5 | 125 | 6.2 ∠63° | - | - | 21.7 ∠-102° | - | - |
| 7 | 175 | 5.0 ∠93° | - | - | 23.5 ∠79° | 24.4 ∠45° | - |
| 9 | 225 | - | - | - | - | - | - |
| 11 | 275 | 18.2 ∠70° | - | - | 23.7 ∠175° | 21.0 ∠159° | - |
| 13 | 325 | 11.9 ∠-150° | - | - | 11.6 ∠-41° | 14.6 ∠-40° | - |
| 15 | 375 | - | - | - | - | - | - |
| 17 | 425 | - | - | - | - | 10.5 ∠-151° | - |
| 19 | 475 | - | - | - | - | - | - |
| 21 | 525 | - | - | - | - | - | - |
| 23 | 575 | - | - | - | - | - | - |
| 25 | 625 | - | - | - | - | - | - |
| 27 | 675 | - | - | - | - | - | - |
| 29 | 725 | - | - | - | - | - | - |
| 31 | 775 | - | - | - | - | - | - |
| 33 | 825 | - | - | - | - | - | - |
| 35 | 875 | - | - | - | 24.4 ∠-134° | - | - |
| 37 | 925 | - | - | - | - | 14.6 ∠-79° | - |
| 39 | 975 | - | - | - | - | - | - |
| 41 | 1025 | - | - | - | - | 21.9 ∠-141° | - |
| 43 | 1075 | - | - | - | - | 26.9 ∠-85° | - |

Notes:

(1) Magnitudes expressed in per unit on 13.8 kV 100 MVA base.
(2) No measurement on M3 feeder BØ.

TABLE 12

BEACH TS (60HZ) 115Kv HARMONIC MEASUREMENTS - NOVEMBER 26, 1987

| TIME | QUANTITY | THD(%) [$I_{fund}$(A RMS)(1)] RØ | WØ | BØ |
|---|---|---|---|---|
| 14:14 | H5K Current | 0.6 [338] | 0.9 [338] | 1.3 [326] |
| 13:49 | H6K Current | 2.8 [343] | 1.8 [360] | 2.0 [346] |
| 13:55 | H6K Current | 0.9 [310] | 1.3 [307] | 1.1 [298] |
| 13:50 | Bus Voltage | 0.9 | 1.3 | 1.1 |
| 13:56 | Bus Voltage | 0.6 | 1.3 | 1.2 |

Notes:
(1) $I_{fund}$ applicable to current measurements only.

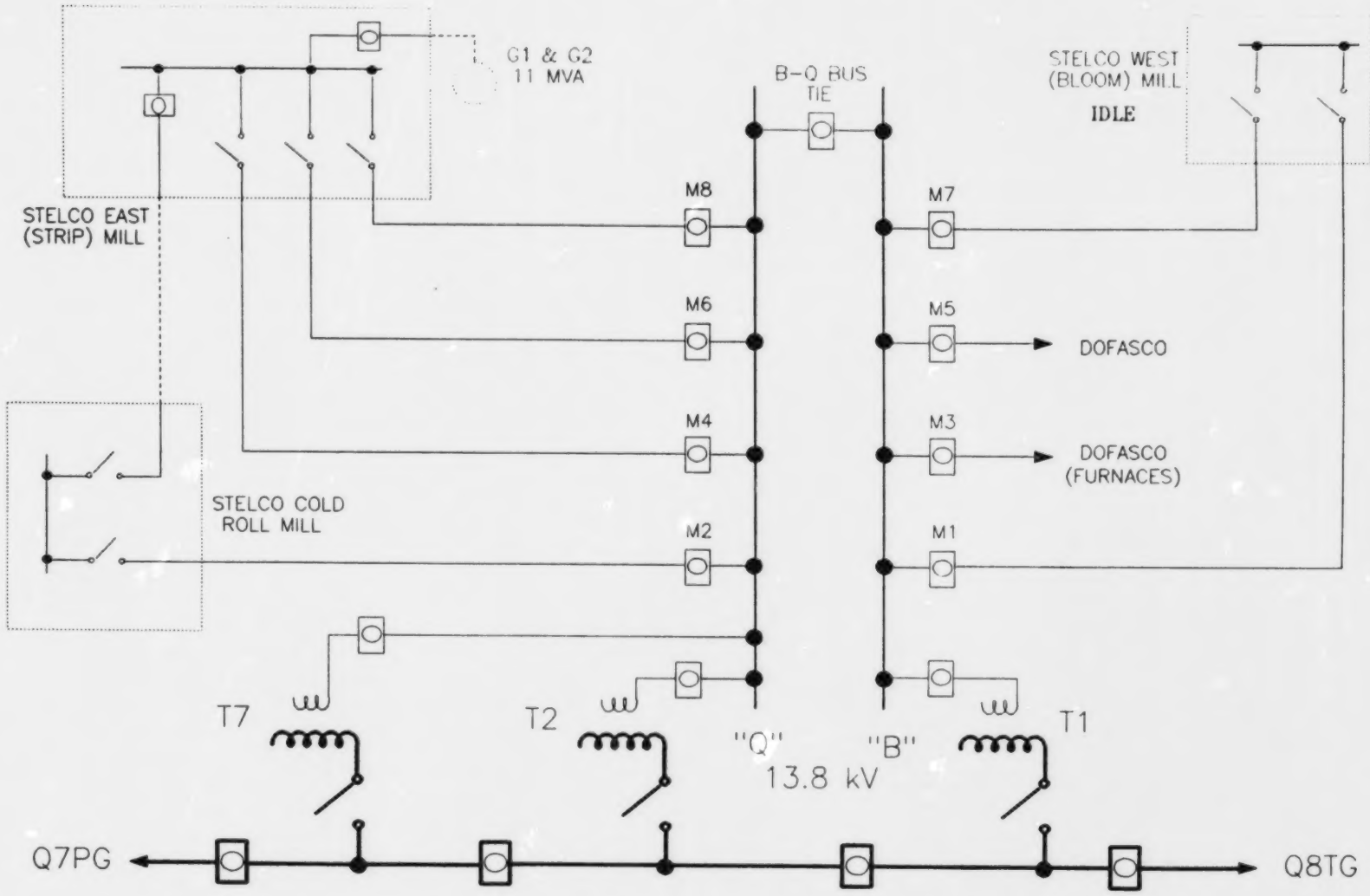


FIGURE 1 : GAGE TS 25 Hz – SIMPLIFIED SINGLE LINE DIAGRAM

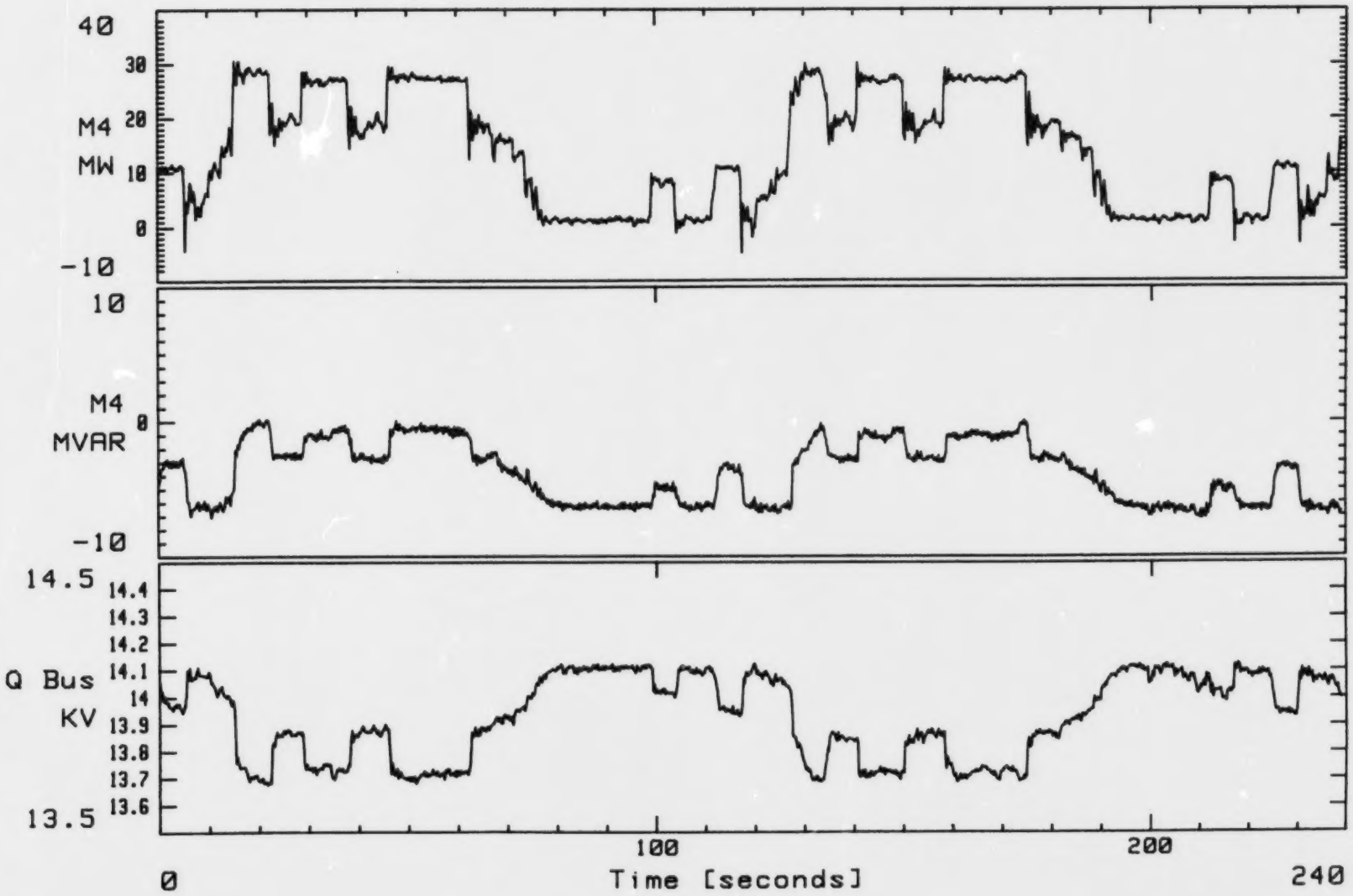


FIGURE 2 : Feeder M4, M6 & M8 – Stelco East Mill
( Nov 23, 1987 – 14:18 )

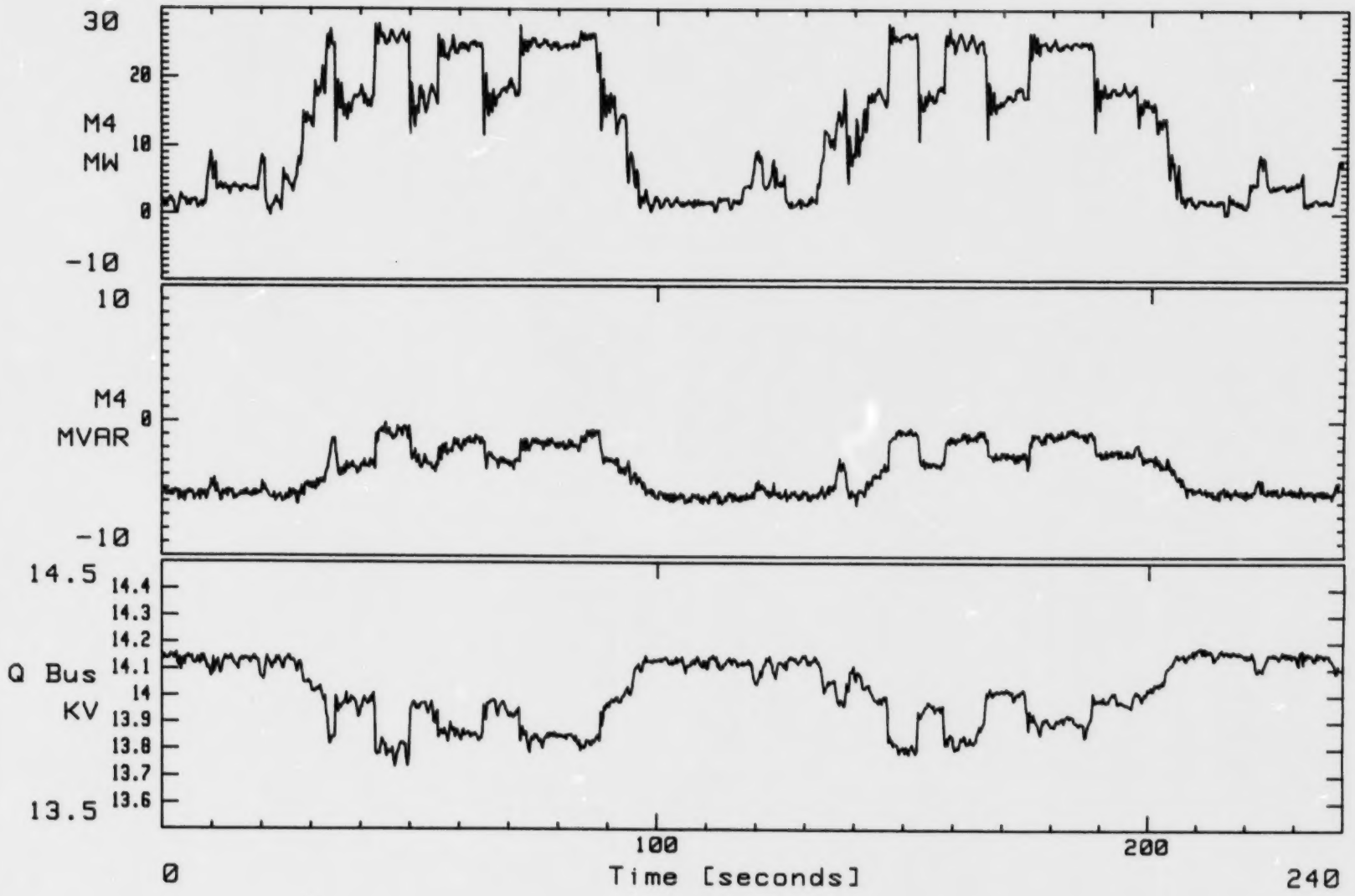


FIGURE 3 : Feeder M4, M6 & M8 – Stelco East Mill
( Nov 20, 1987 – 15:13 )

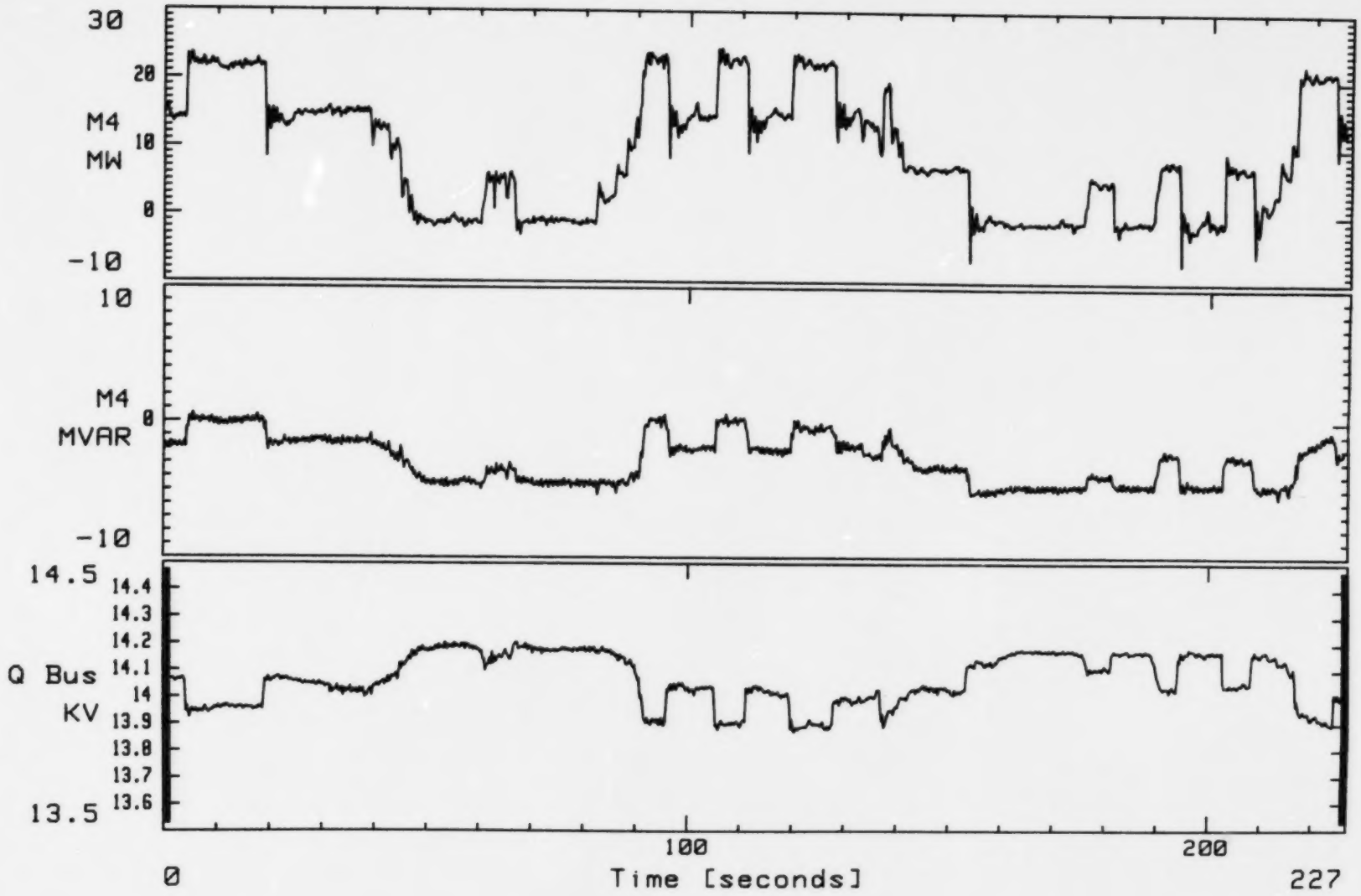


FIGURE 4(a) : Feeder M4, M6 & M8 – Stelco East Mill
( Nov 20, 1987 – 13:48 )

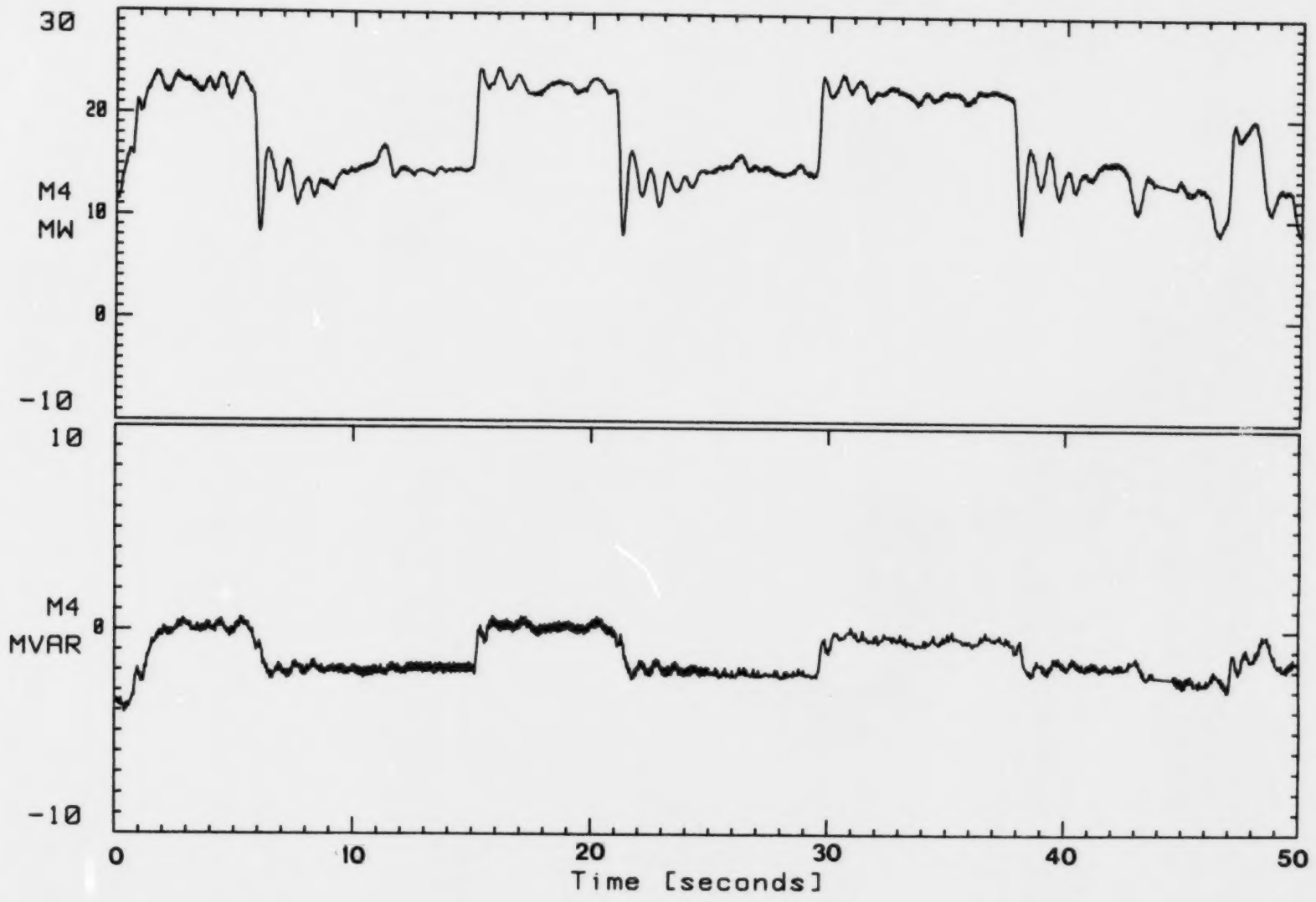


FIGURE 4(b) : Feeder M4, M6 & M8 – Stelco East Mill
( Nov 20, 1987 – 13:48 )

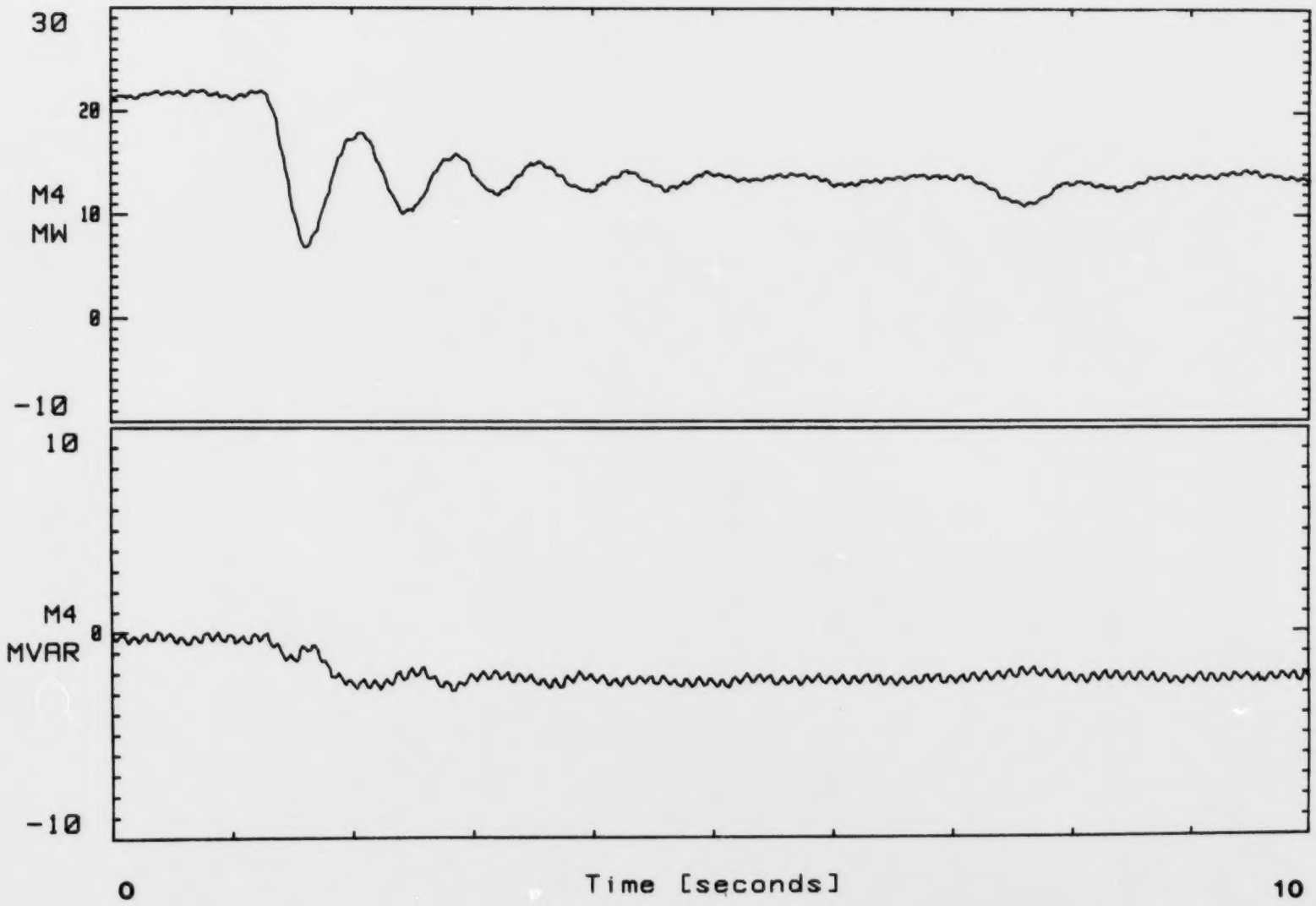


FIGURE 5 : Feeder M4, M6 & M8 – Stelco East Mill
Oscillations Following Load Step Change

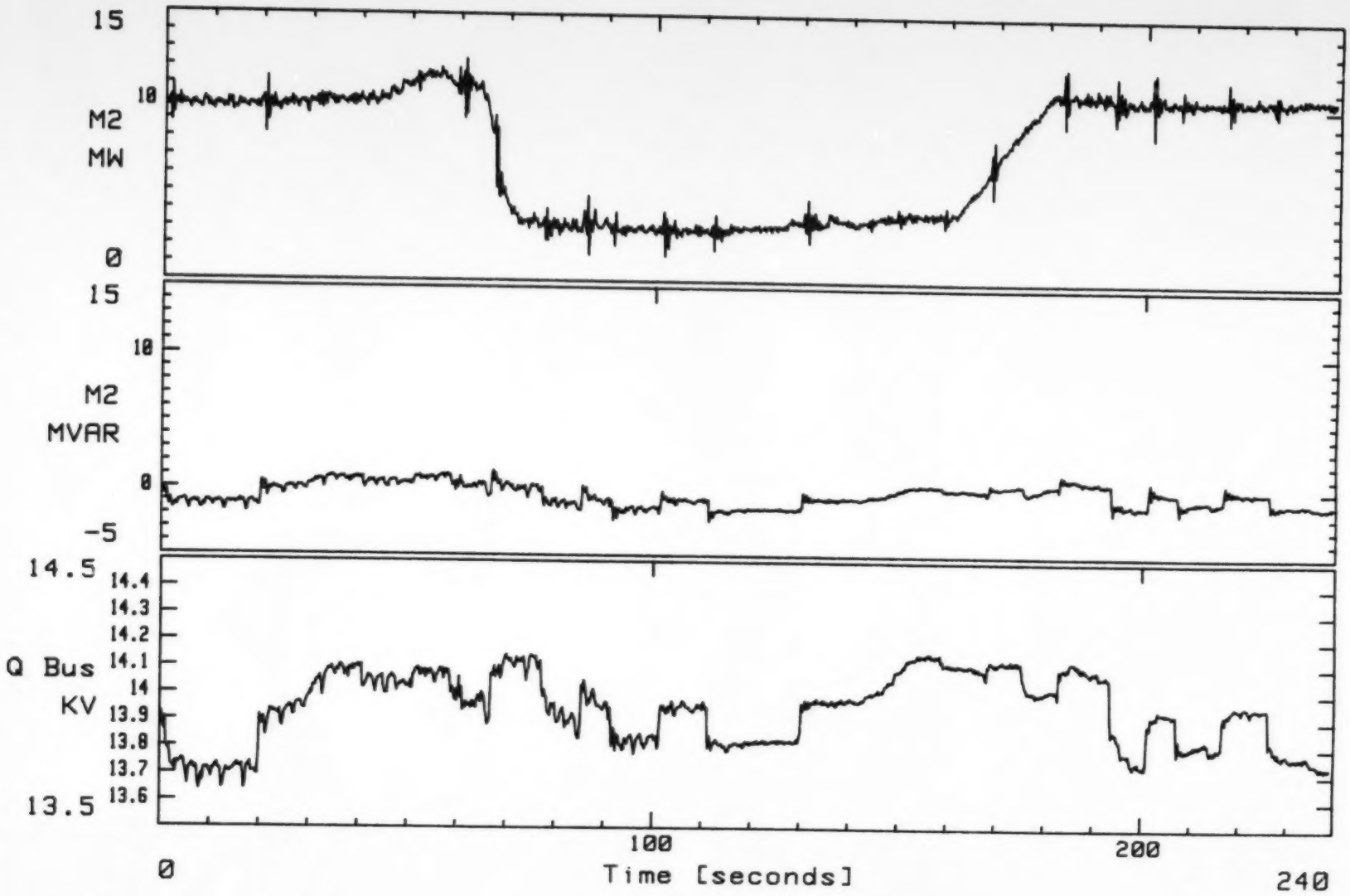


FIGURE 6 : Feeder M2 – Stelco Cold Roll Mill
( Nov 23, 1987 – 11:08 )

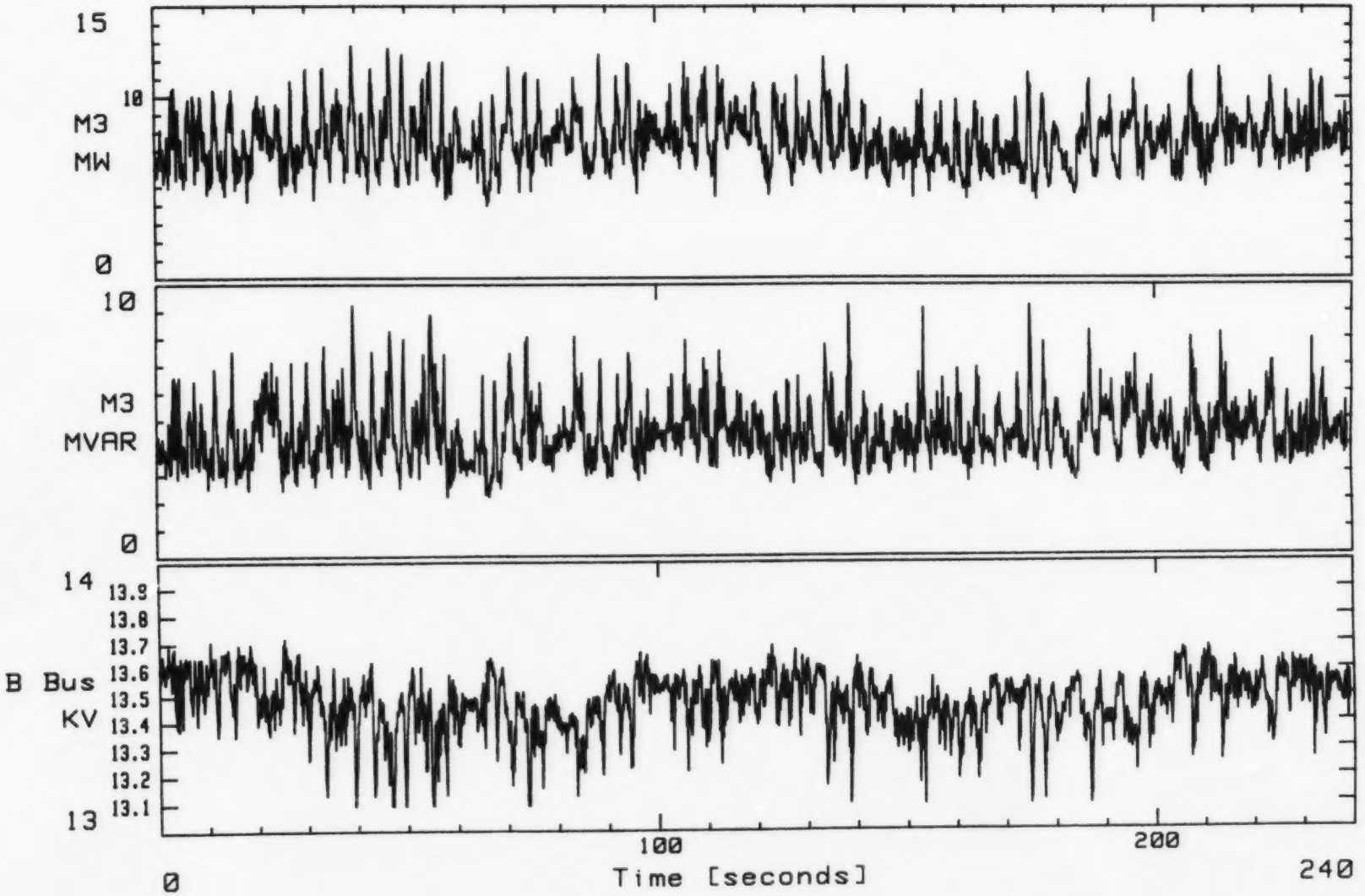


FIGURE 7 : Feeder M3 – Dofasco Arc Furnaces
( Nov 20, 1987 – 15:13 )

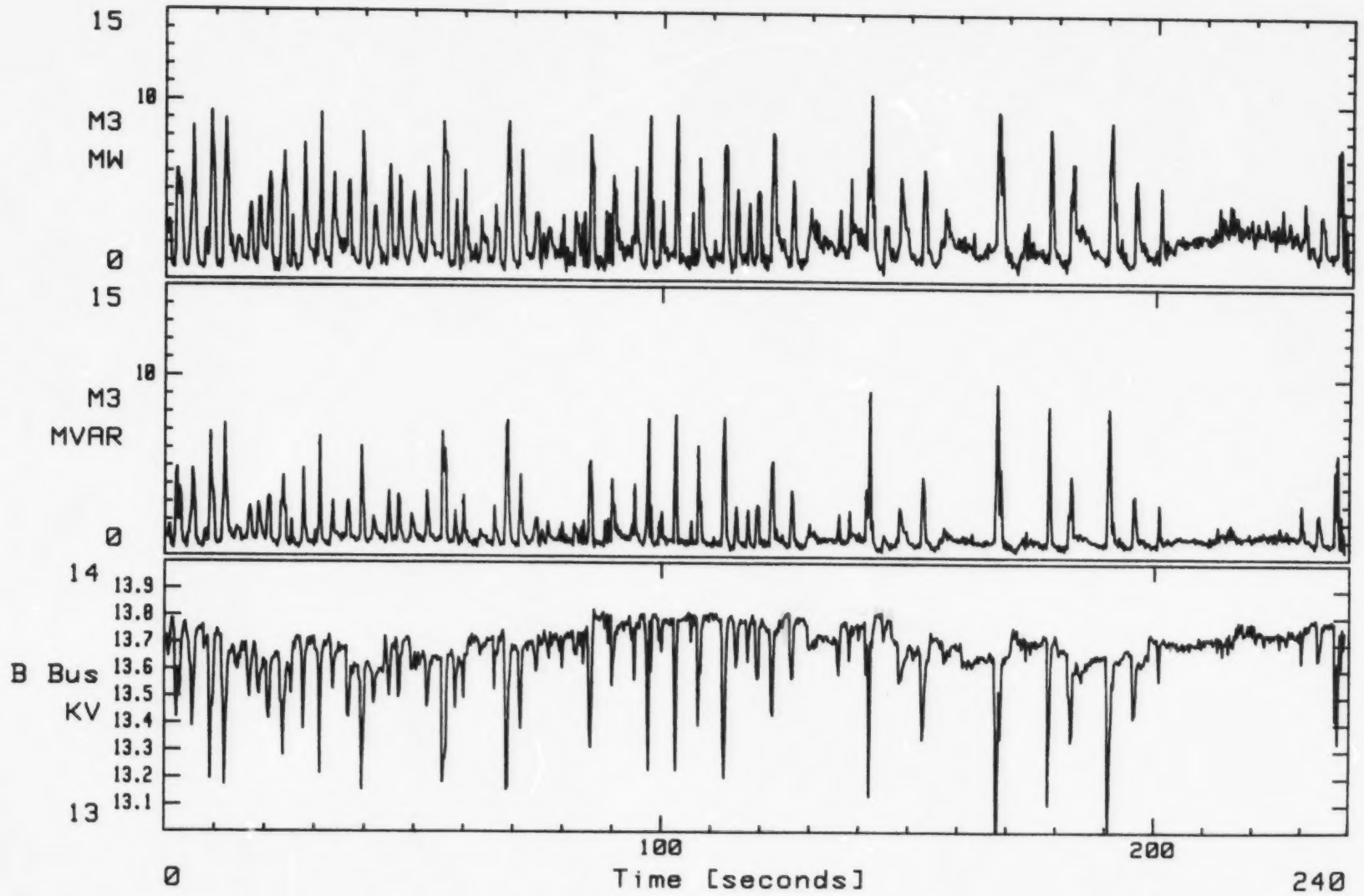


FIGURE 8 : Feeder M3 – Dofasco Arc Furnaces
( Nov 23, 1987 – 11:15 )

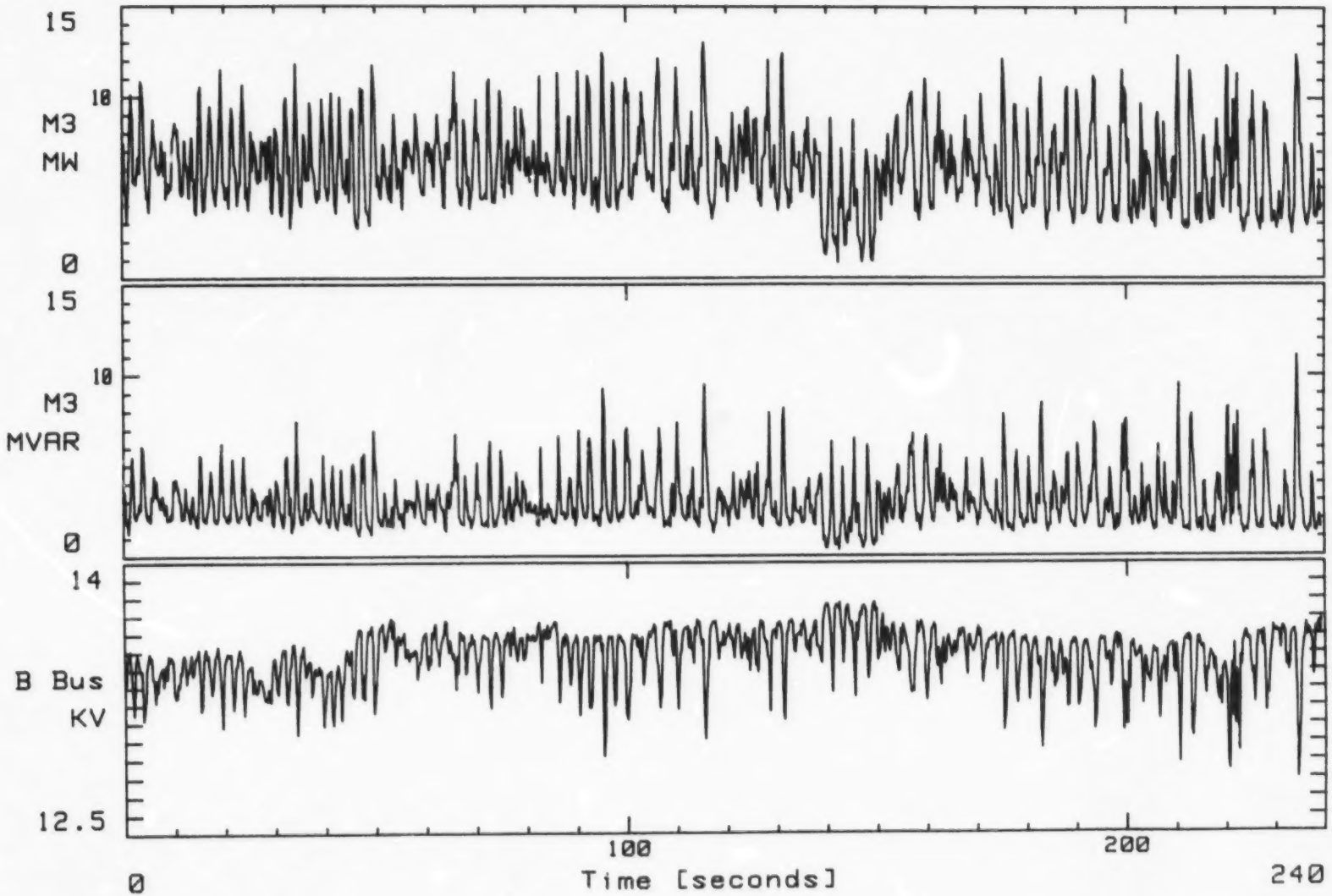


FIGURE 9 : Feeder M3 – Dofasco Arc Furnaces
( Nov 23, 1987 – 13:41 )

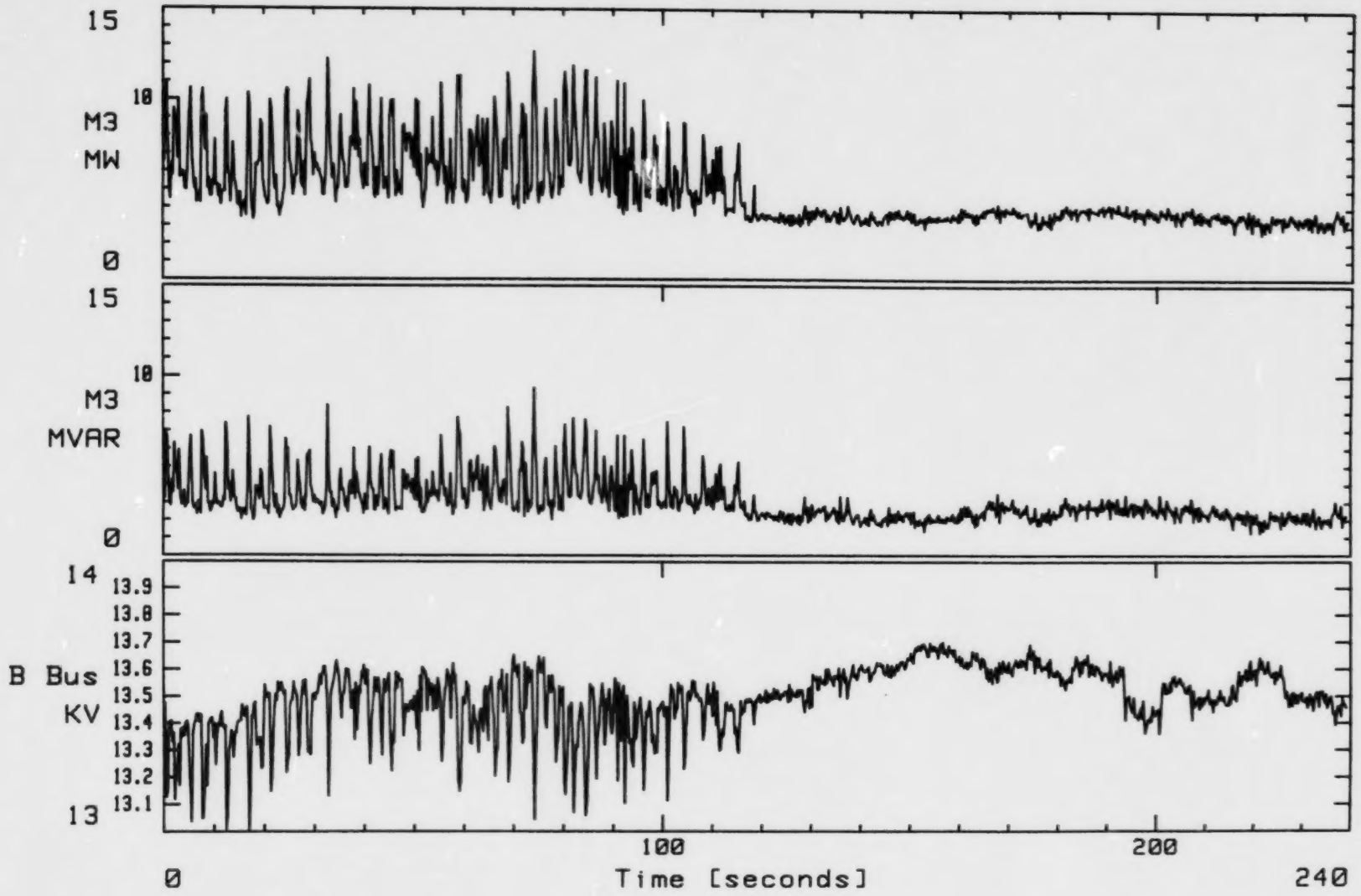


FIGURE 10 : Feeder M3 – Dofasco Arc Furnaces
( Nov 23, 1987 – 11:08 )

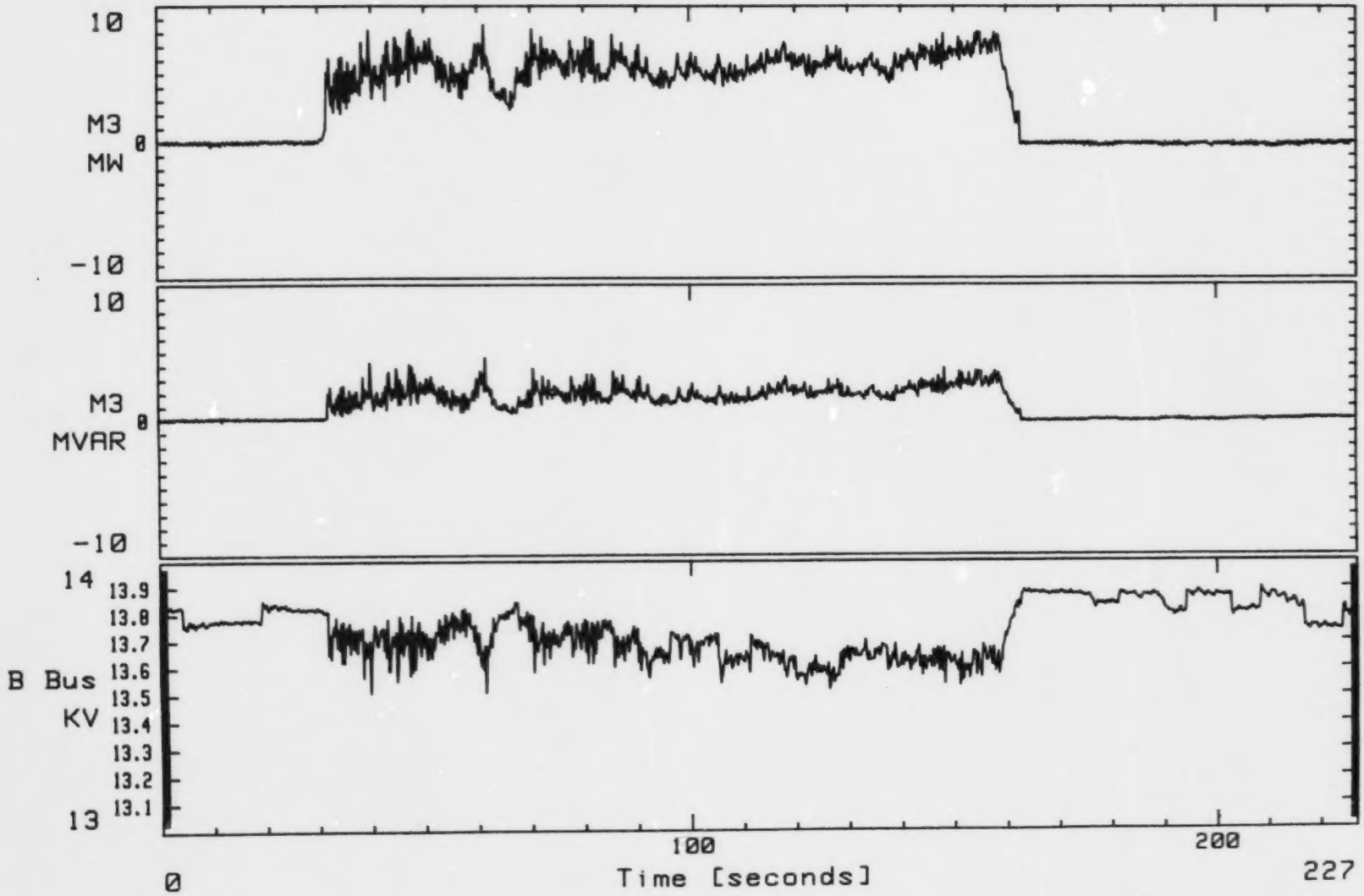


FIGURE 11 : Feeder M3 – Dofasco Arc Furnaces
( Nov 20, 1987 – 13:48 )

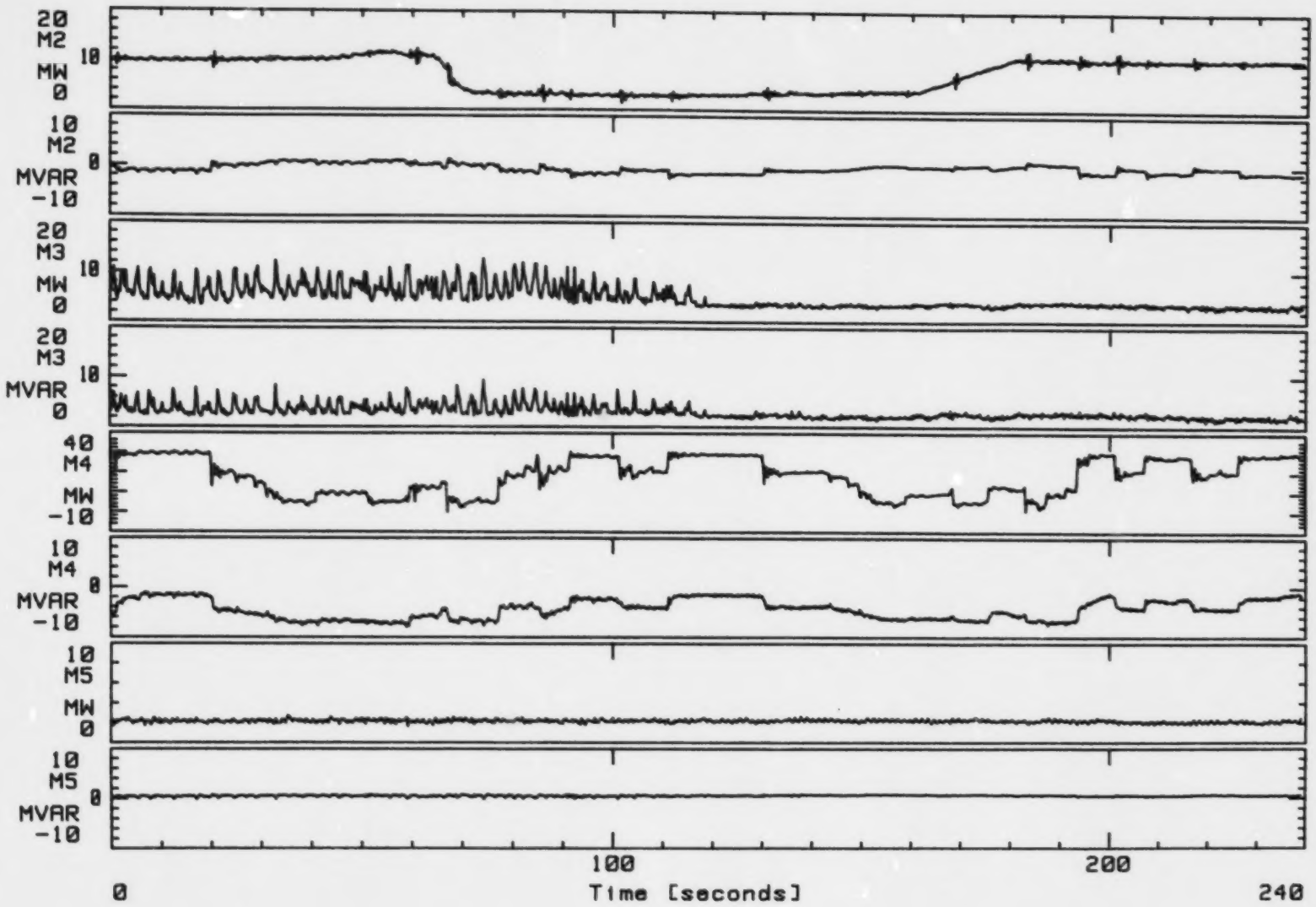


FIGURE 12(a) : Gage TS – Station Total Measurements
( Nov 23, 1987 – 11:08 )

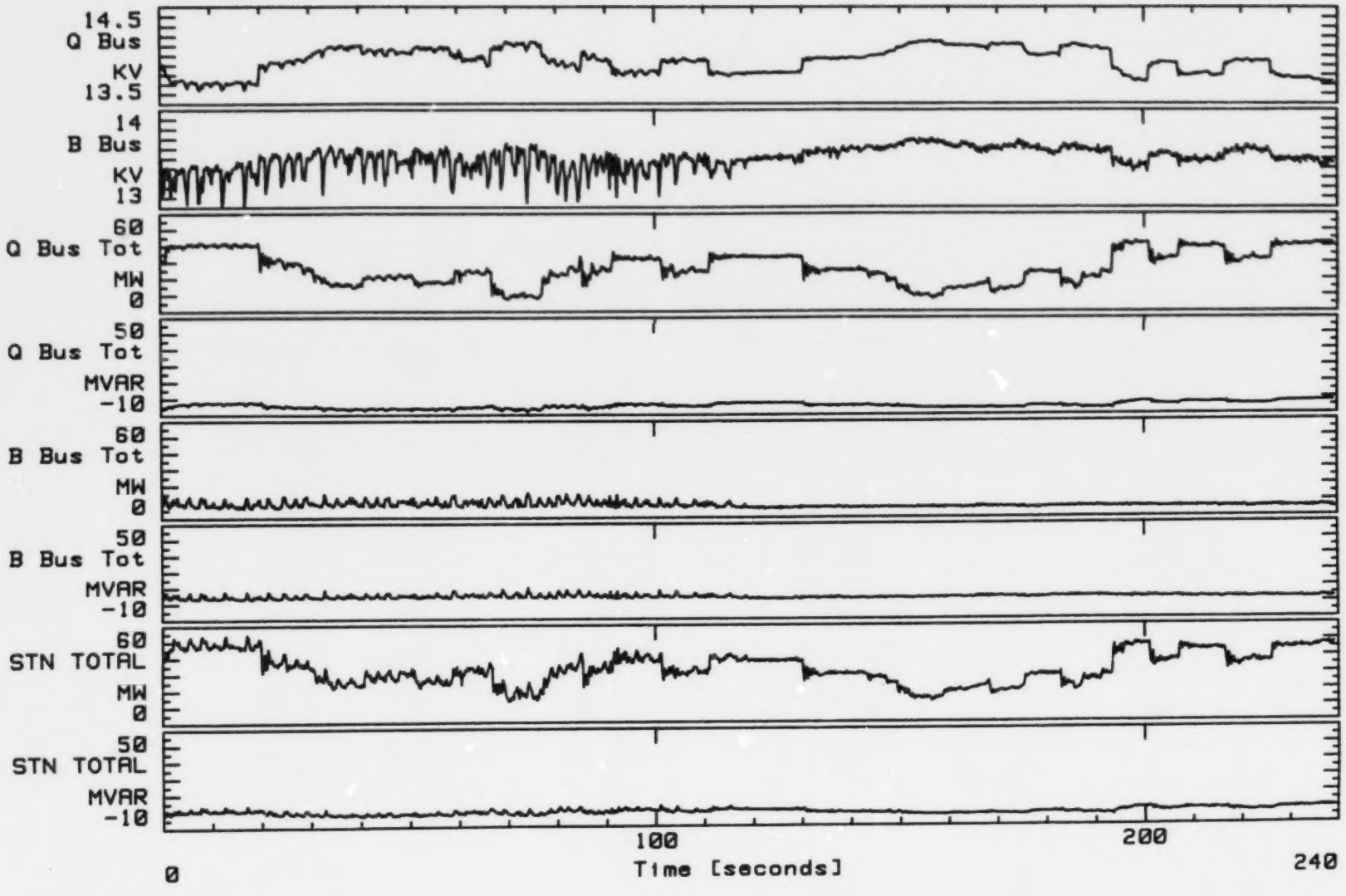


FIGURE 12(b) : Gage TS – Station Total Measurements
( Nov 23, 1987 – 11:08 )

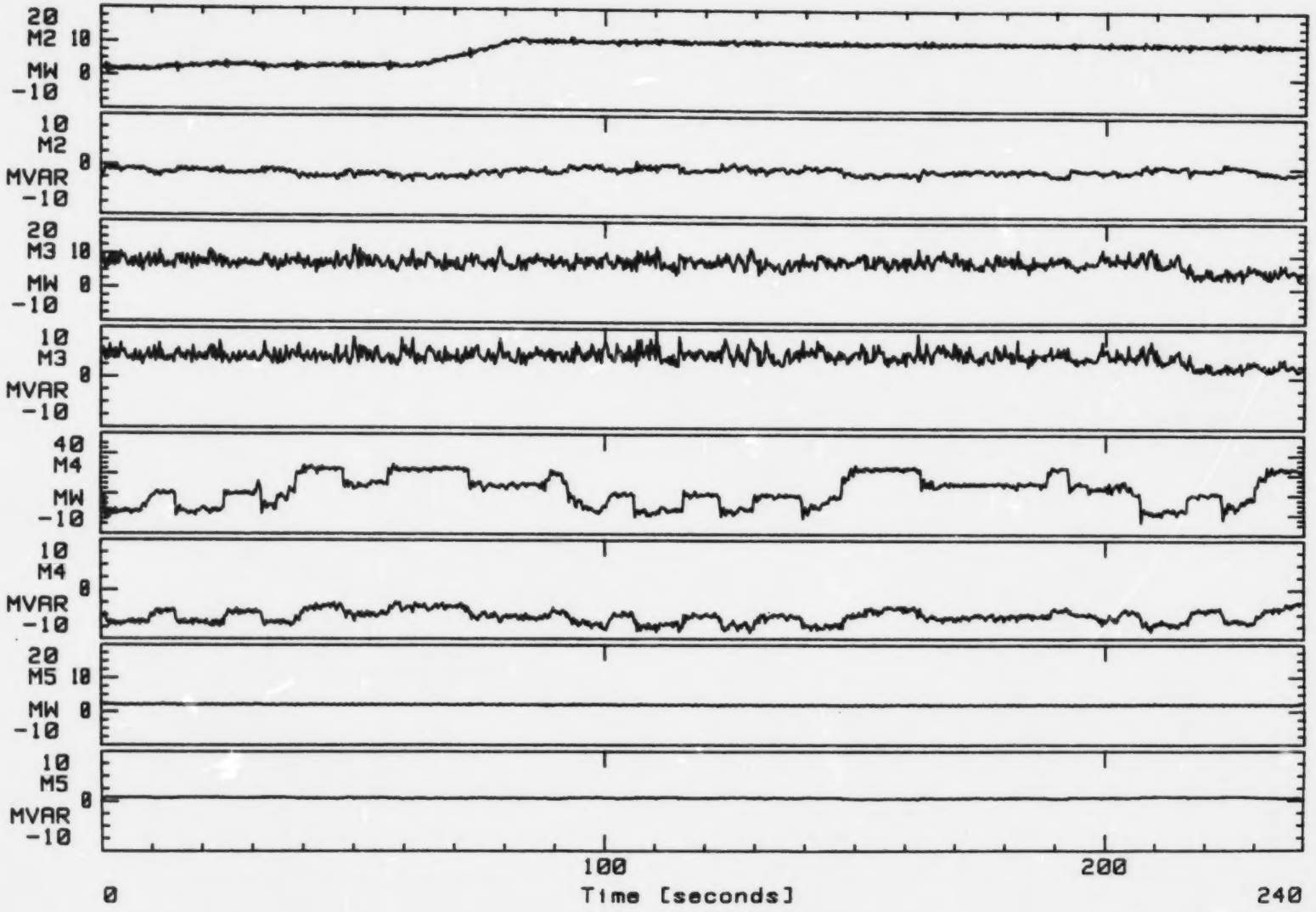


FIGURE 13(a) : Gage TS – Station Total Measurements
( Nov 27, 1987 – 14:20 )

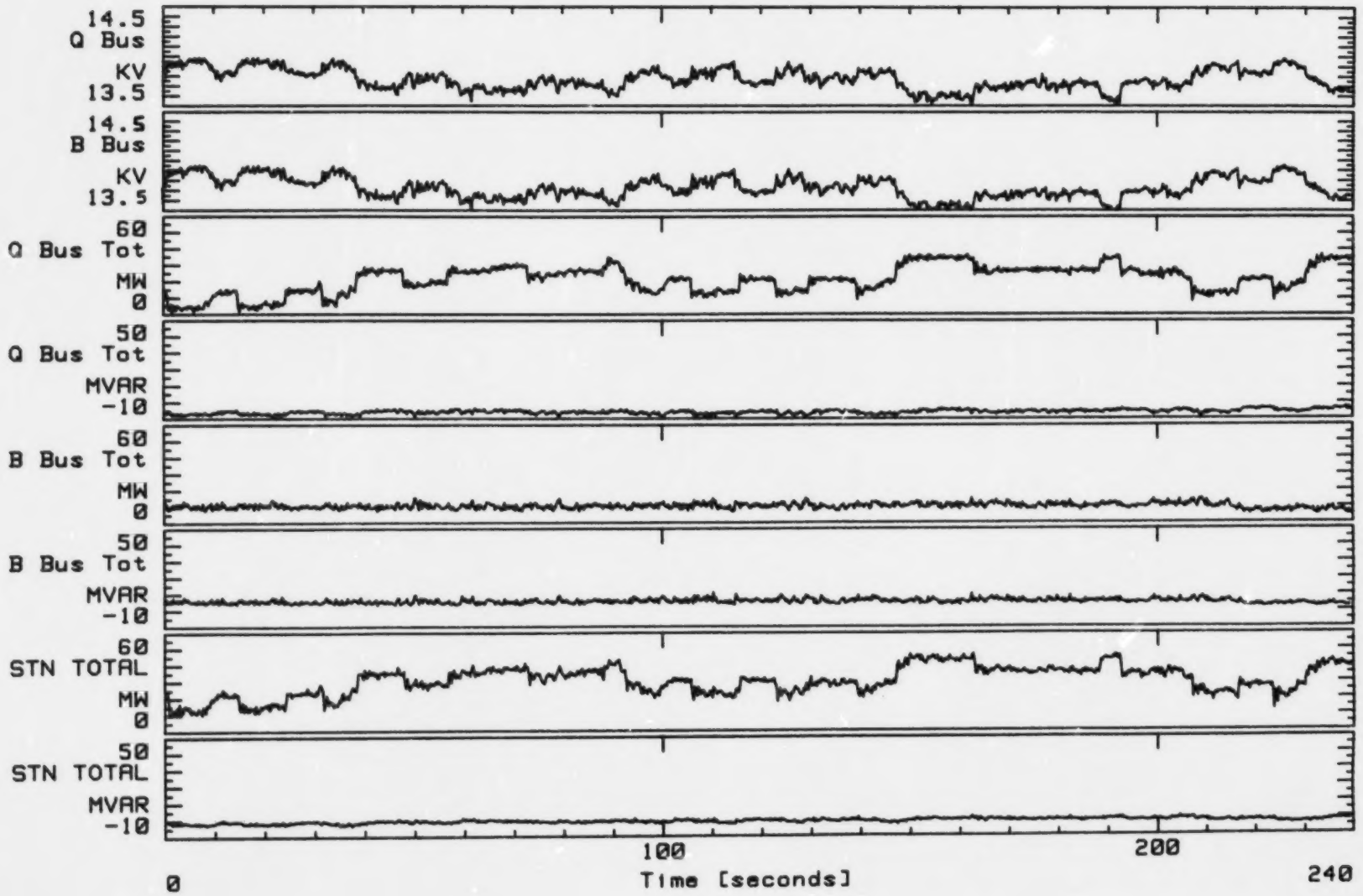


FIGURE 13(b) : Gage TS – Station Total Measurements
( Nov 27, 1987 – 14:20 )

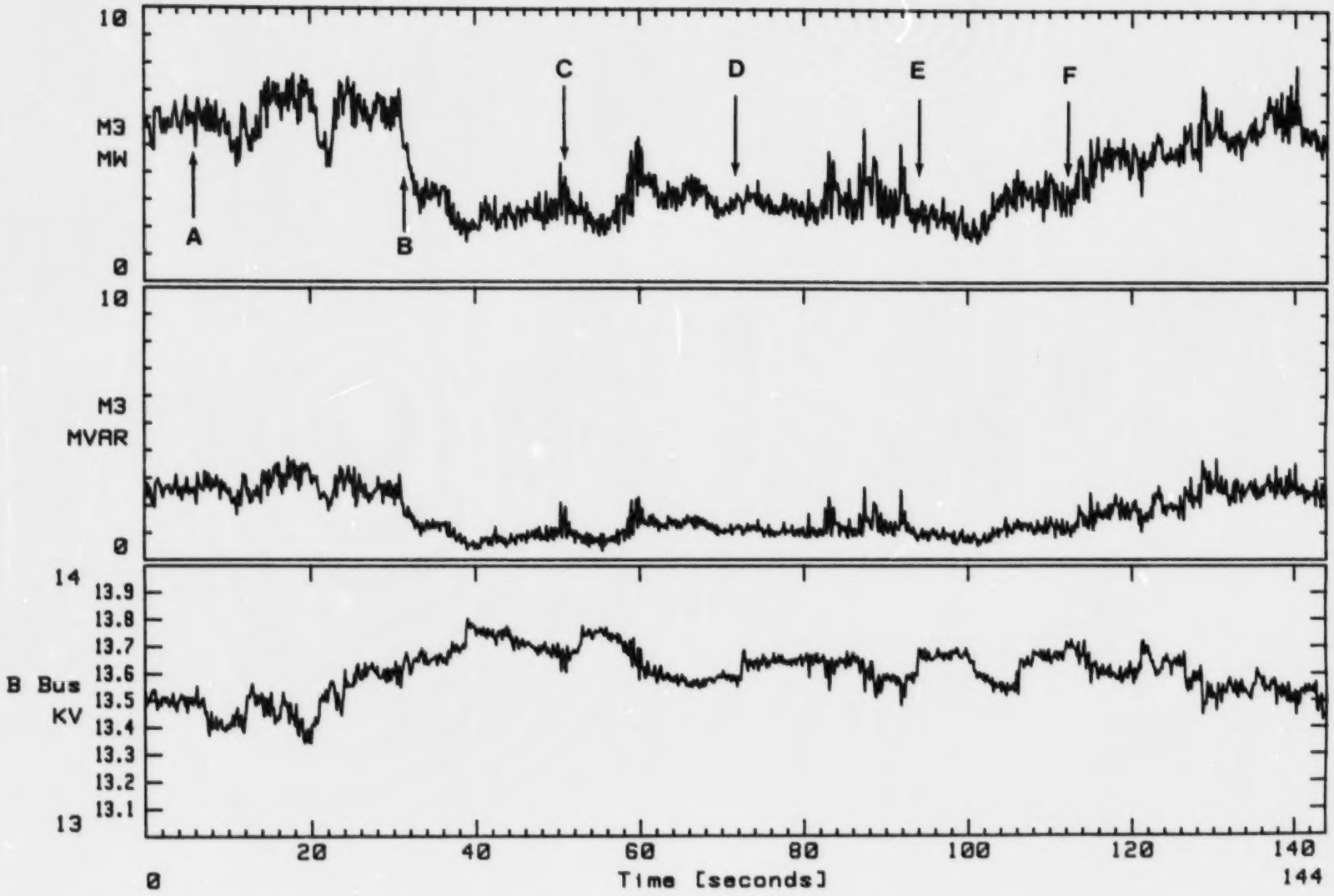


FIGURE 14 : M3 – Load Profile During Harmonic Measurements
( Nov 25, 1987 – 14:04 )

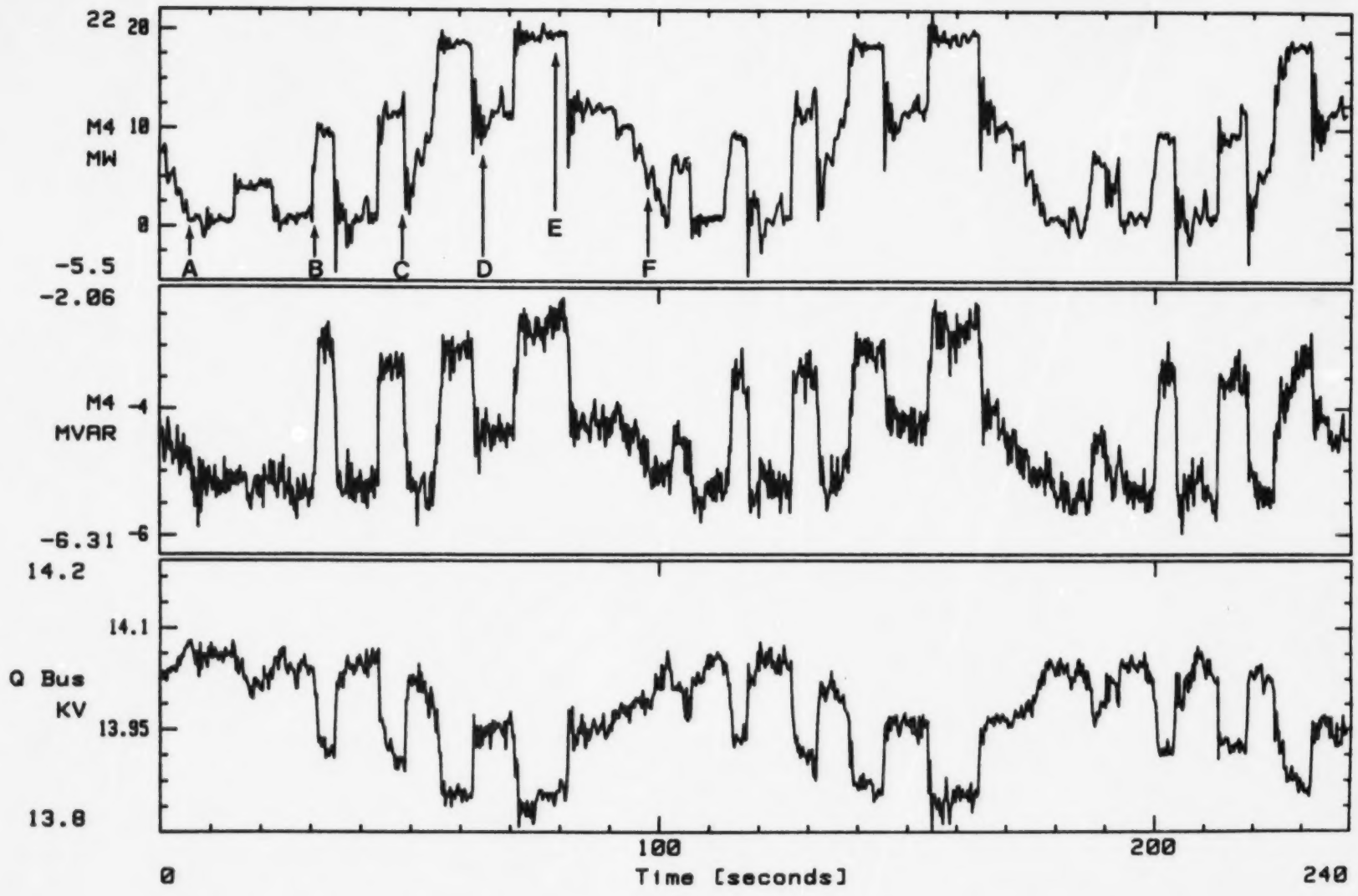


FIGURE 15 : M4 – Load Profile During Harmonic Measurements
( Nov 26, 1987 – 09:31 )

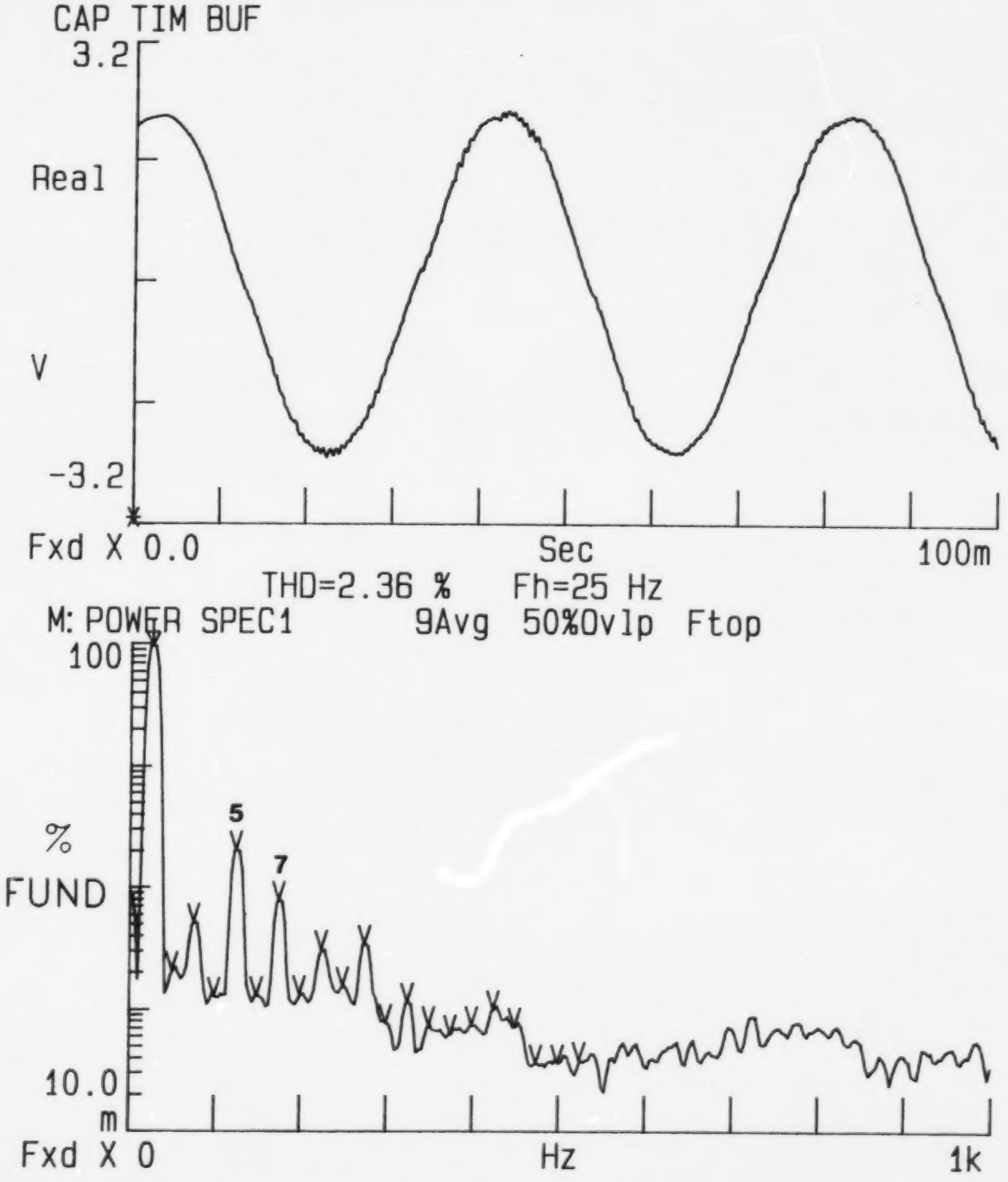


FIGURE 16 : Gage TS 25 Hz. B Bus Voltage
R-W Phase. Nov 25, 1987 14:05

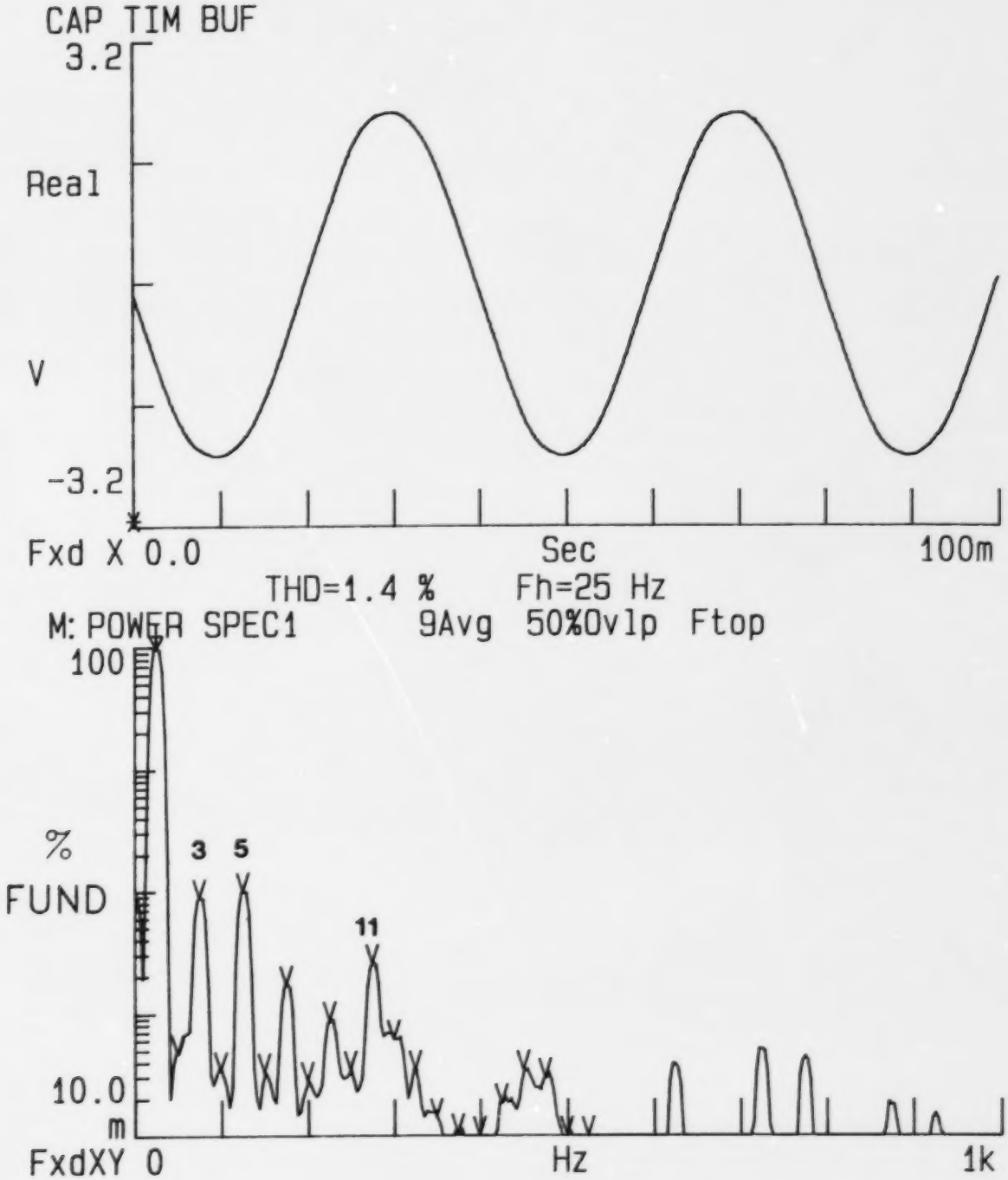


FIGURE 17 : Gage TS 25 Hz. Q Bus Voltage
B–R Phase. Nov 26, 1987 09:32

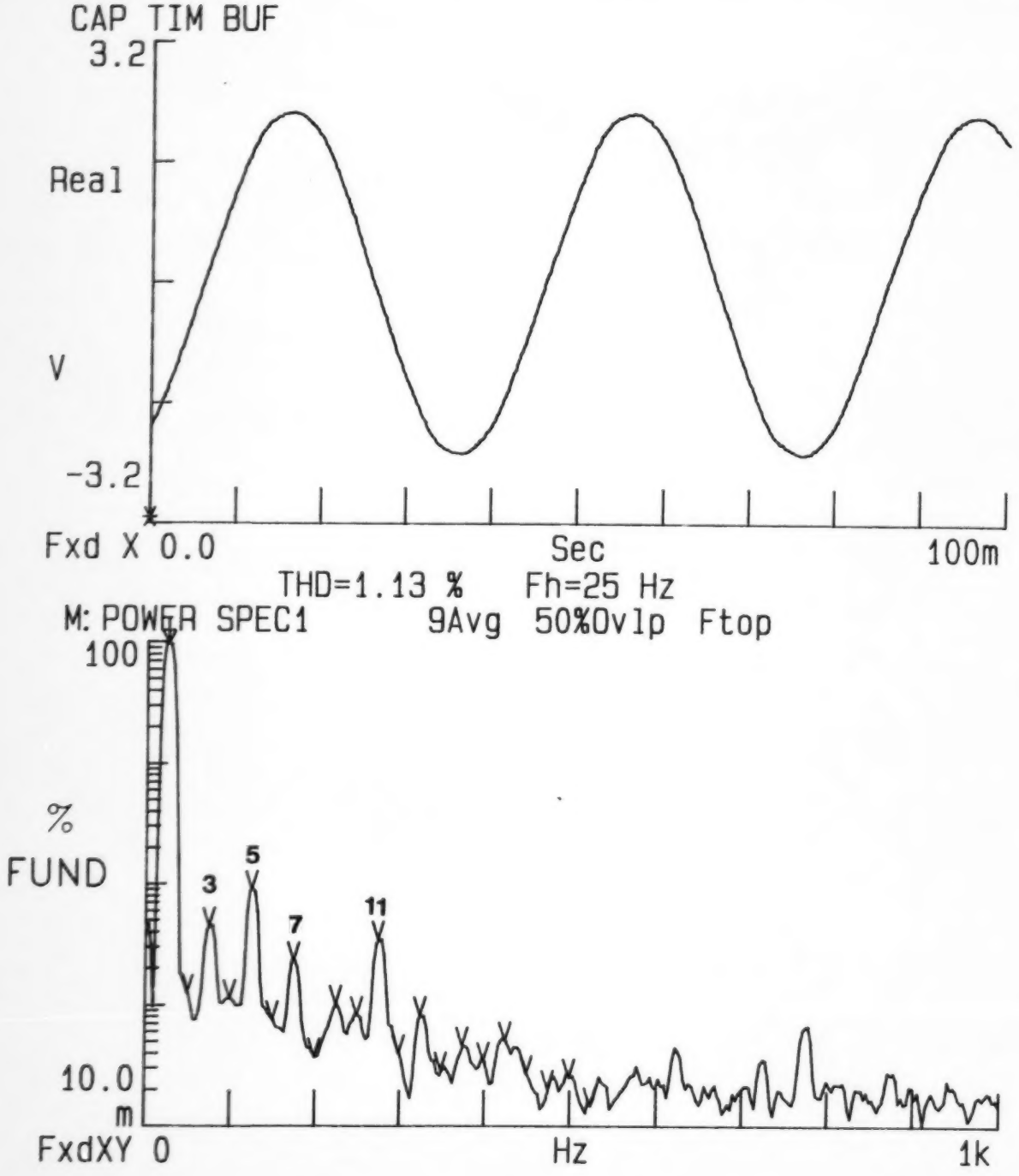


FIGURE 18 : Gage TS 25 Hz. Bus Voltage
( Bus Tie-Breaker Closed )
W-B Phase. Nov 27, 1987 14:18

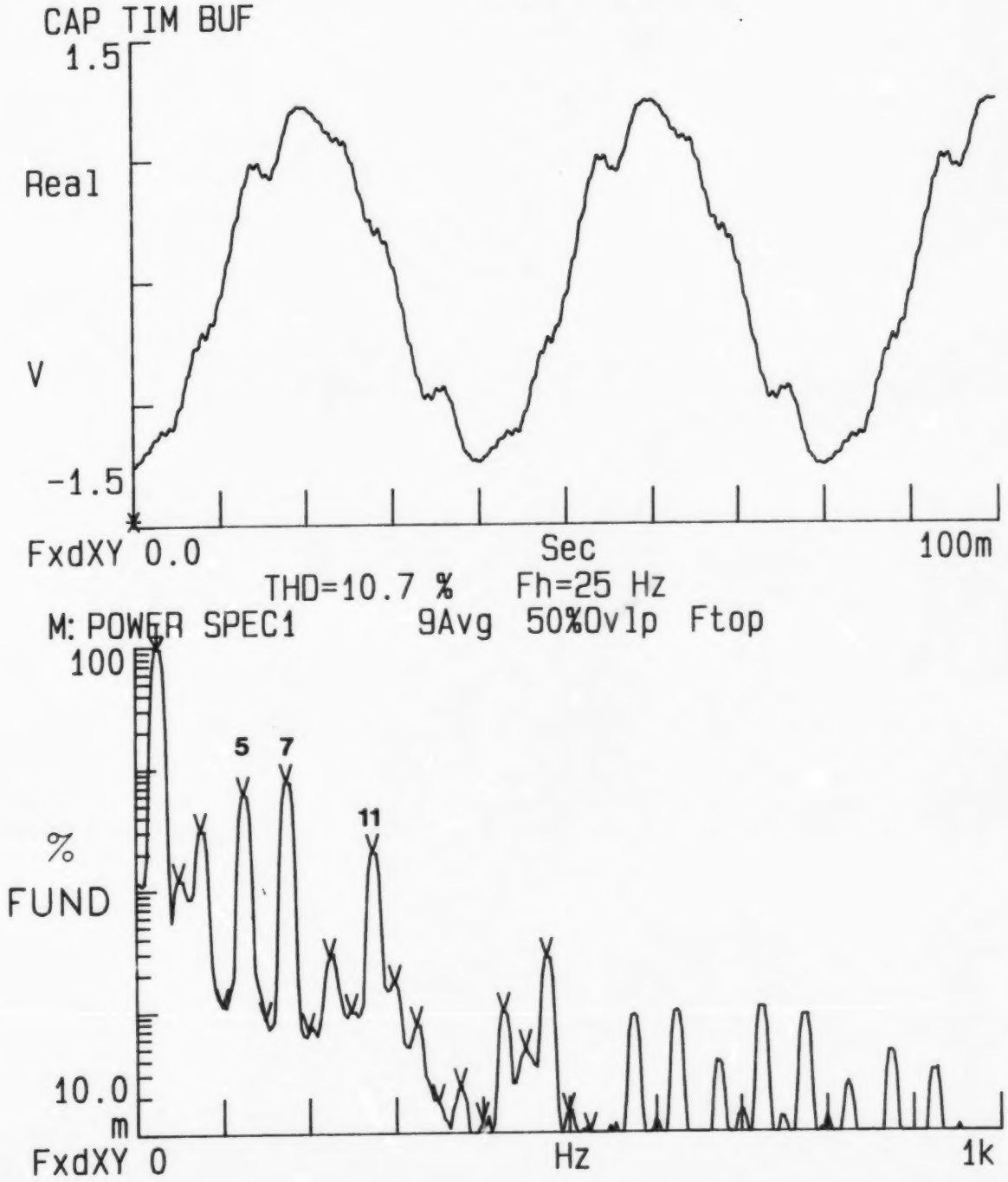


FIGURE 19 : Gage TS 25 Hz. M2 Feeder Current W Phase. Nov 25, 1987 11:20

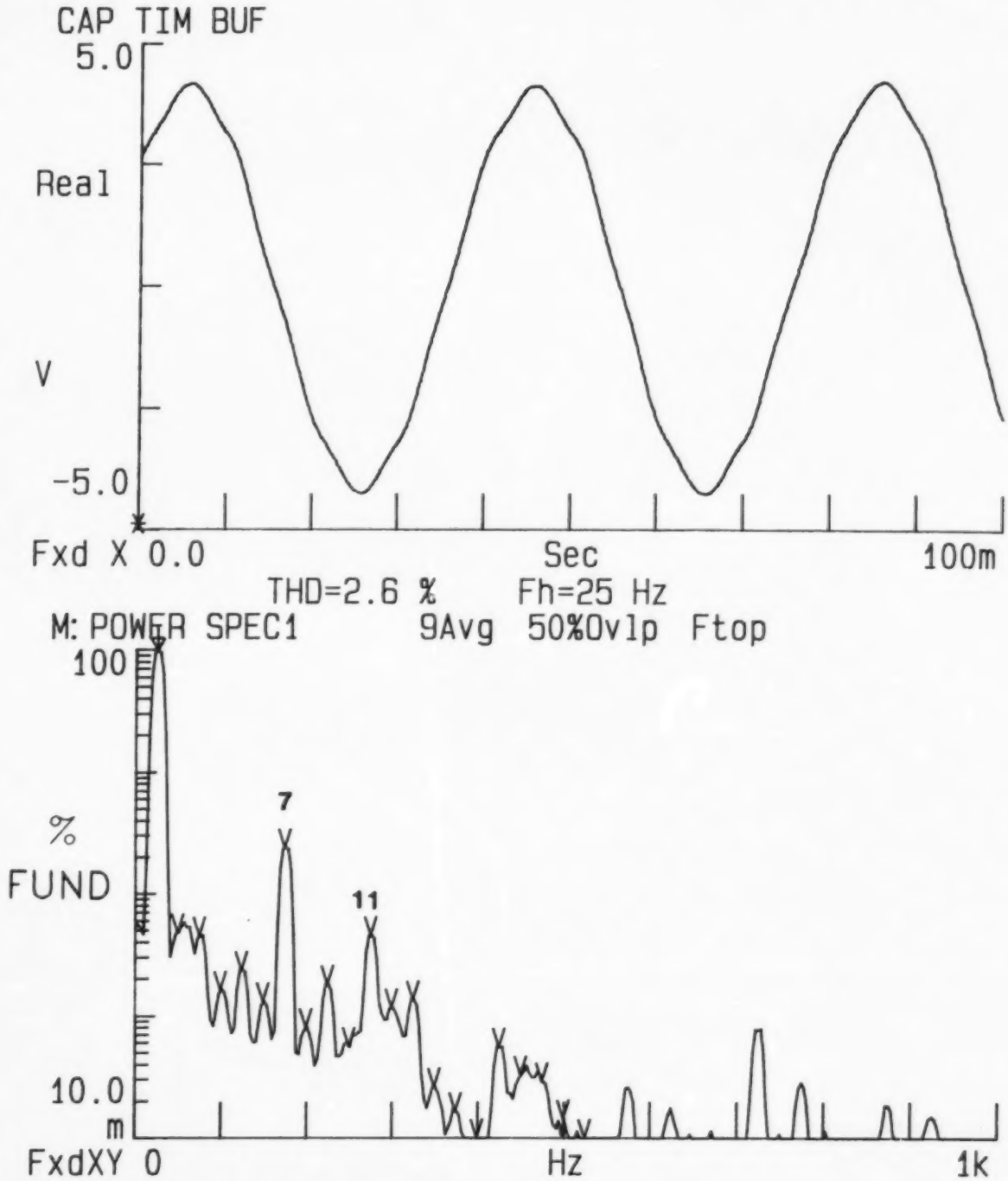


FIGURE 20 : Gage TS 25 Hz. M2 Feeder Current R Phase. Nov 25, 1987 11:41

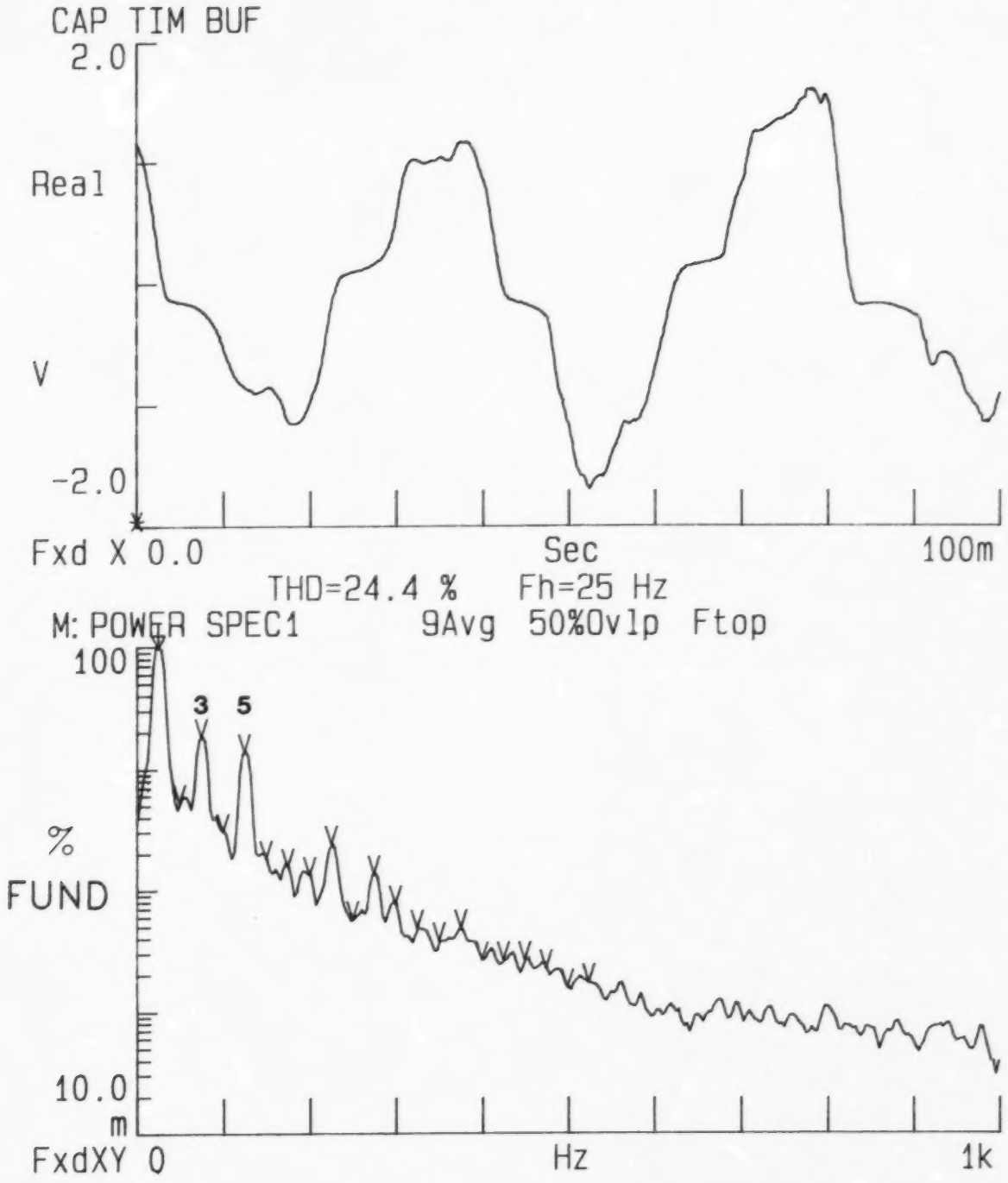


FIGURE 21 : Gage TS 25 Hz. M3 Feeder Current B Phase. Nov 25, 1987 14:05

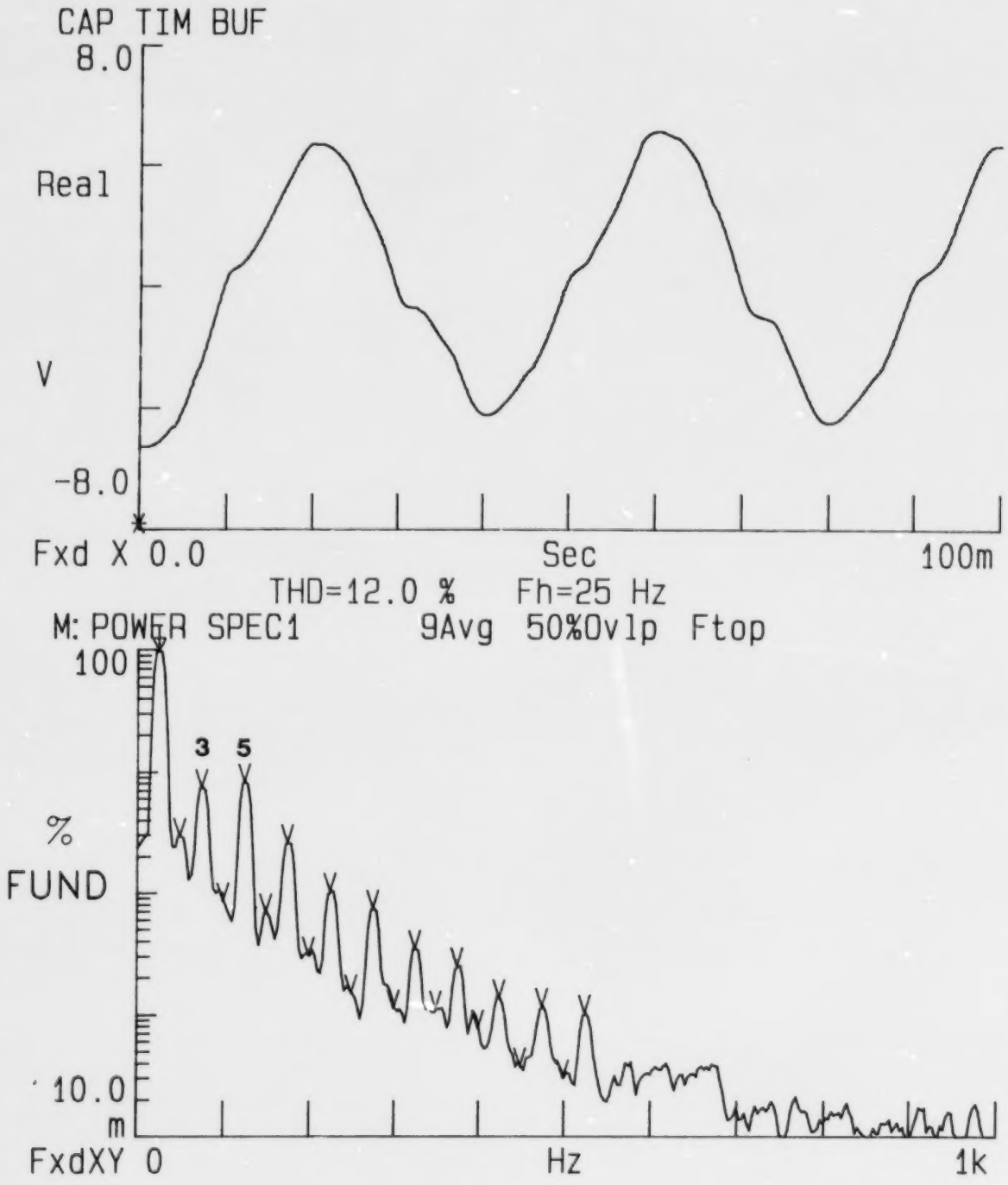


FIGURE 22 : Gage TS 25 Hz. M3 Feeder Current W Phase. Nov 25, 1987 14:23

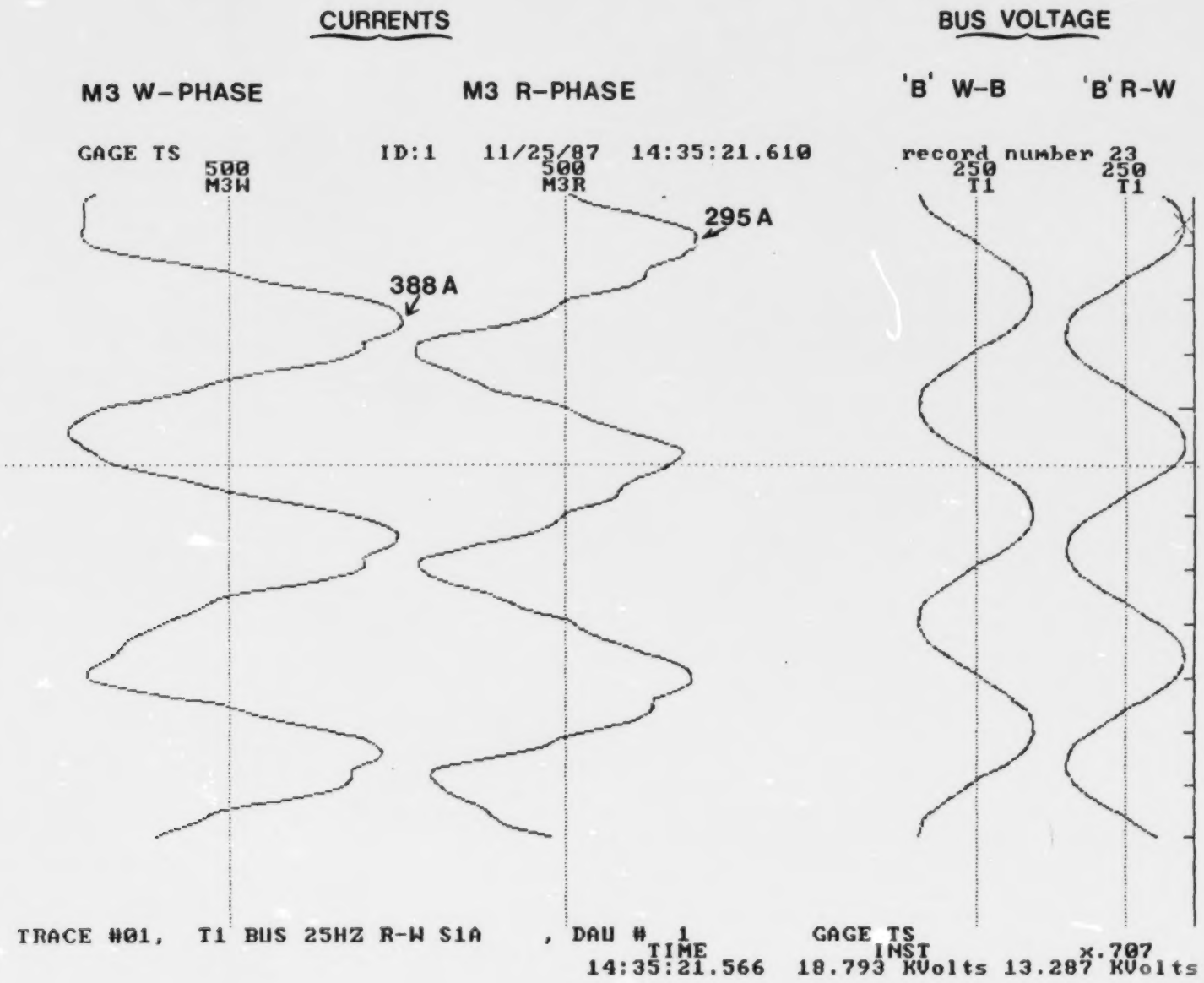


FIGURE 23 : Gage TS 25 Hz. M3 Feeder Current
Nov 25, 1987 14:35

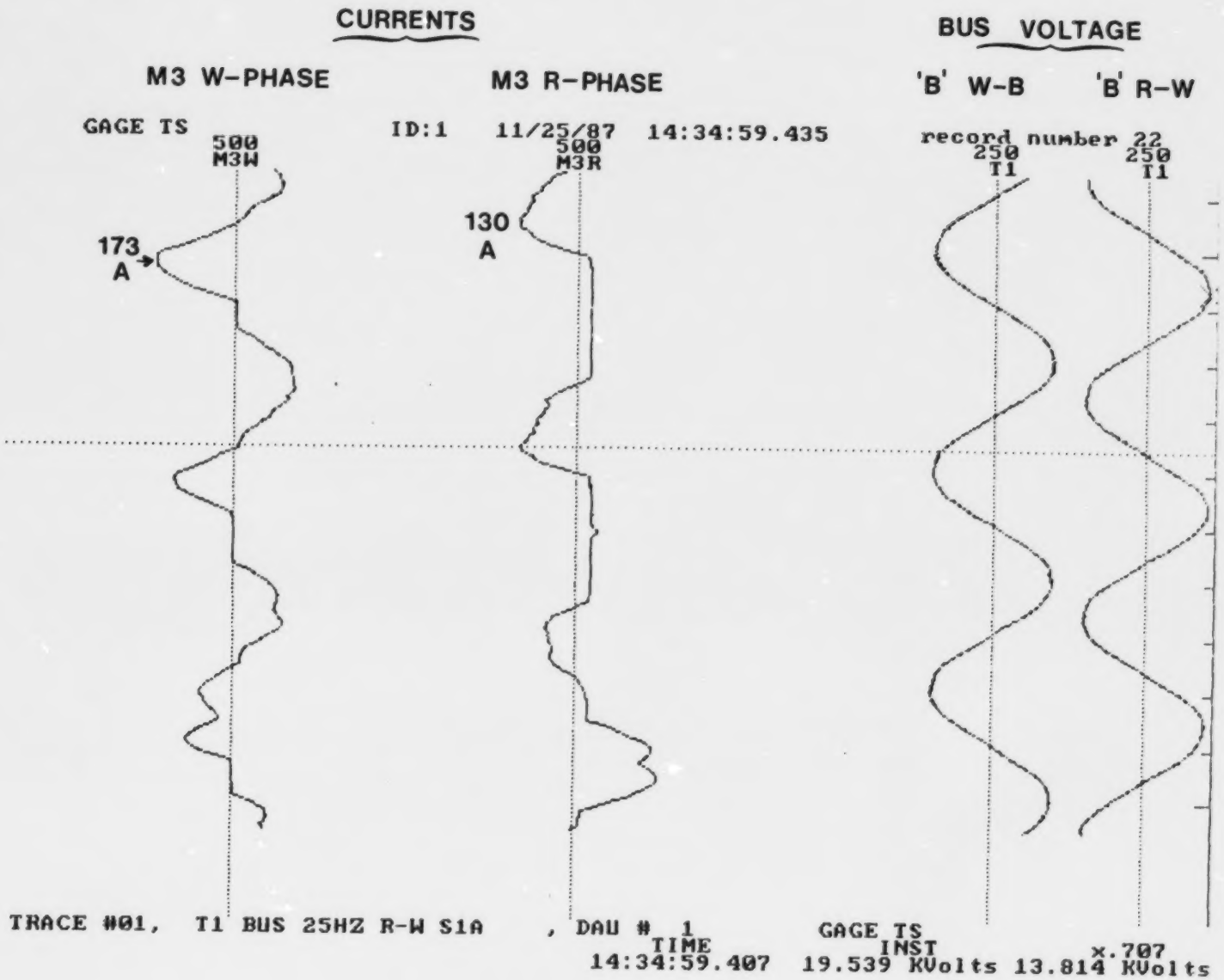


FIGURE 24 : Gage TS 25 Hz. M3 Feeder Current
Nov 25, 1987 14:34

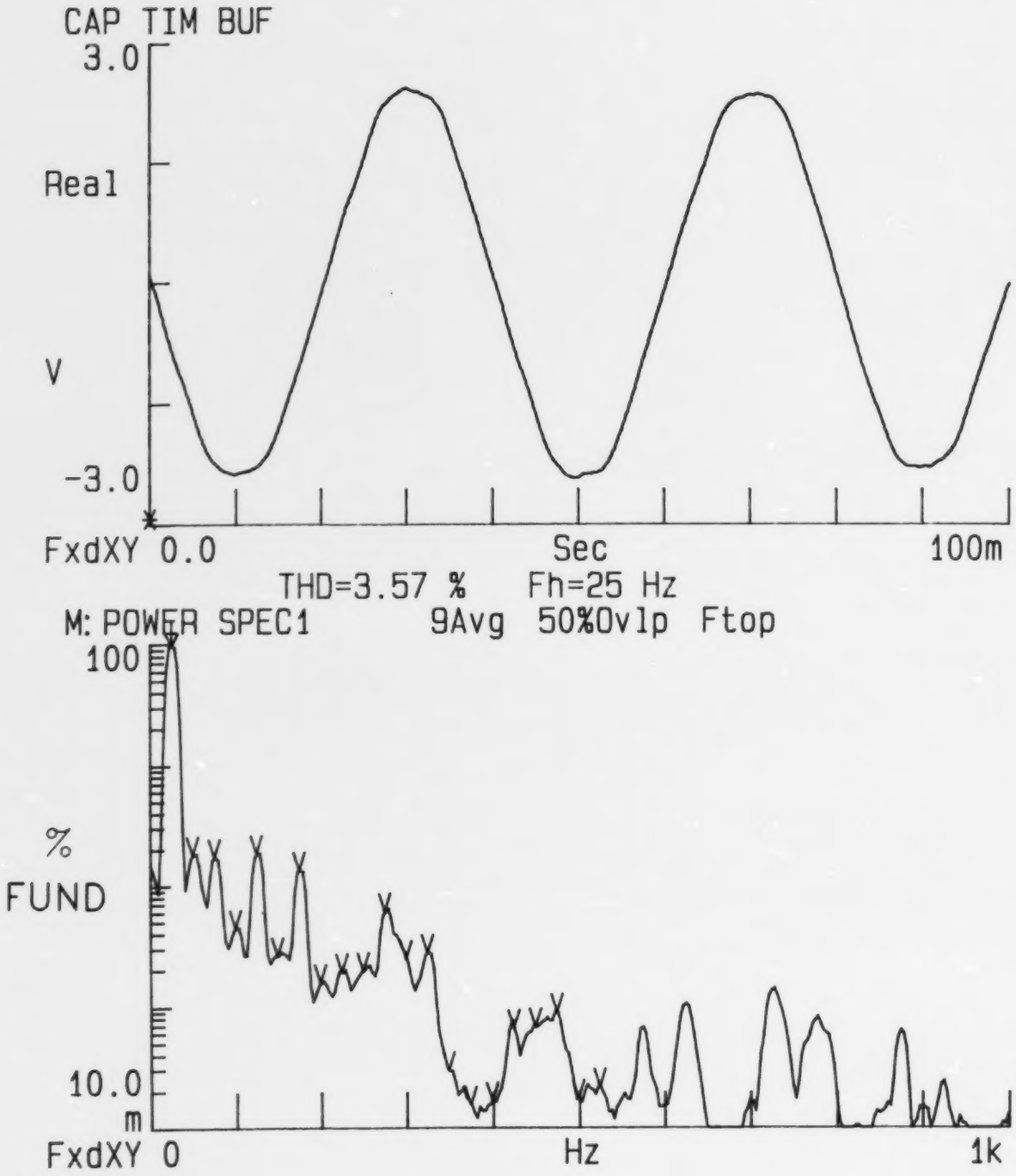


FIGURE 25 : Gage TS 25 Hz. M4 Feeder Current B Phase. Nov 26, 1987 09:32

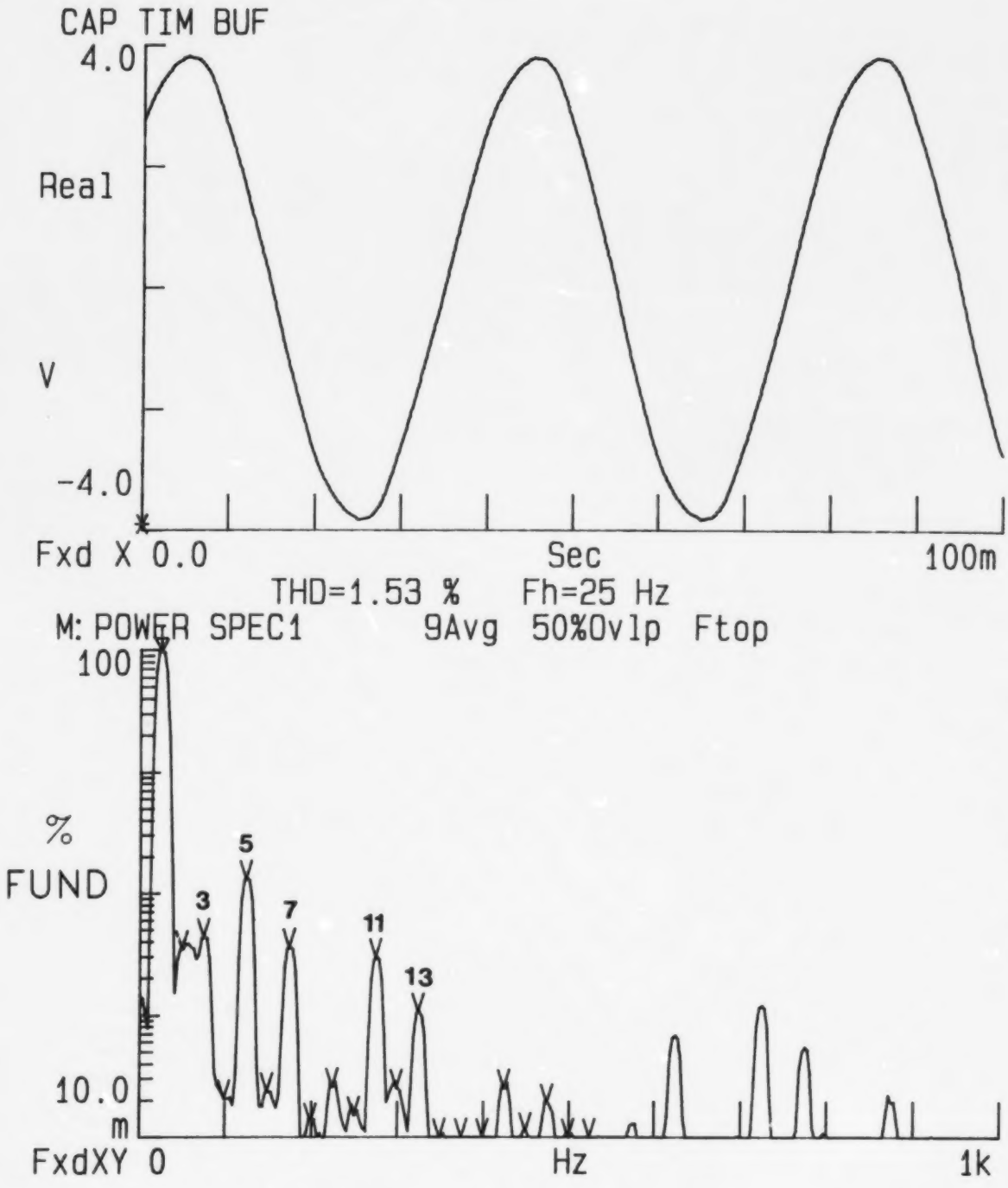


FIGURE 26 : Gage TS 25 Hz. M4 Feeder Current R Phase. Nov 26, 1987 10:33

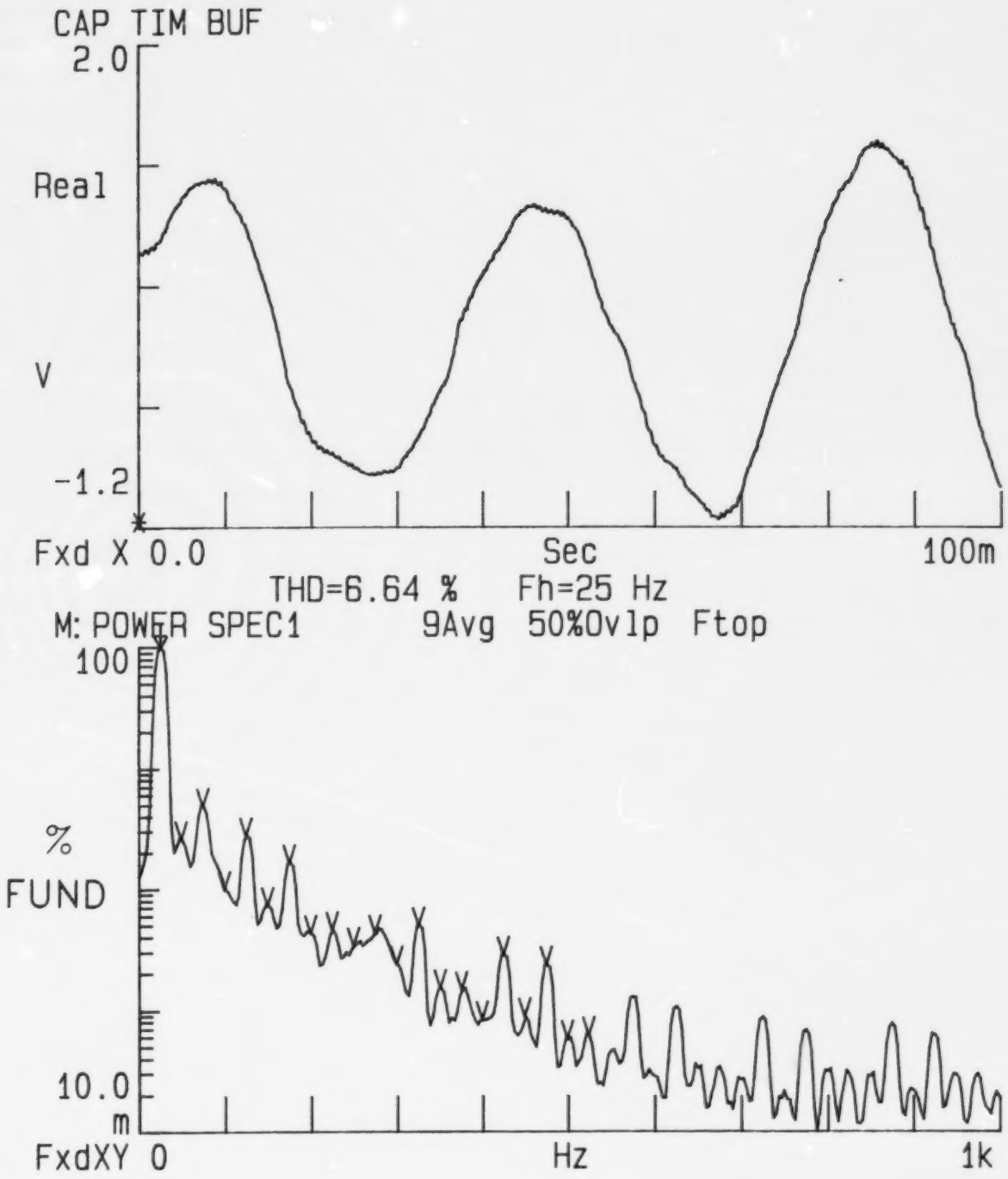


FIGURE 27 : Gage TS 25 Hz. M5 Feeder Current R Phase. Nov 26, 1987 09:51

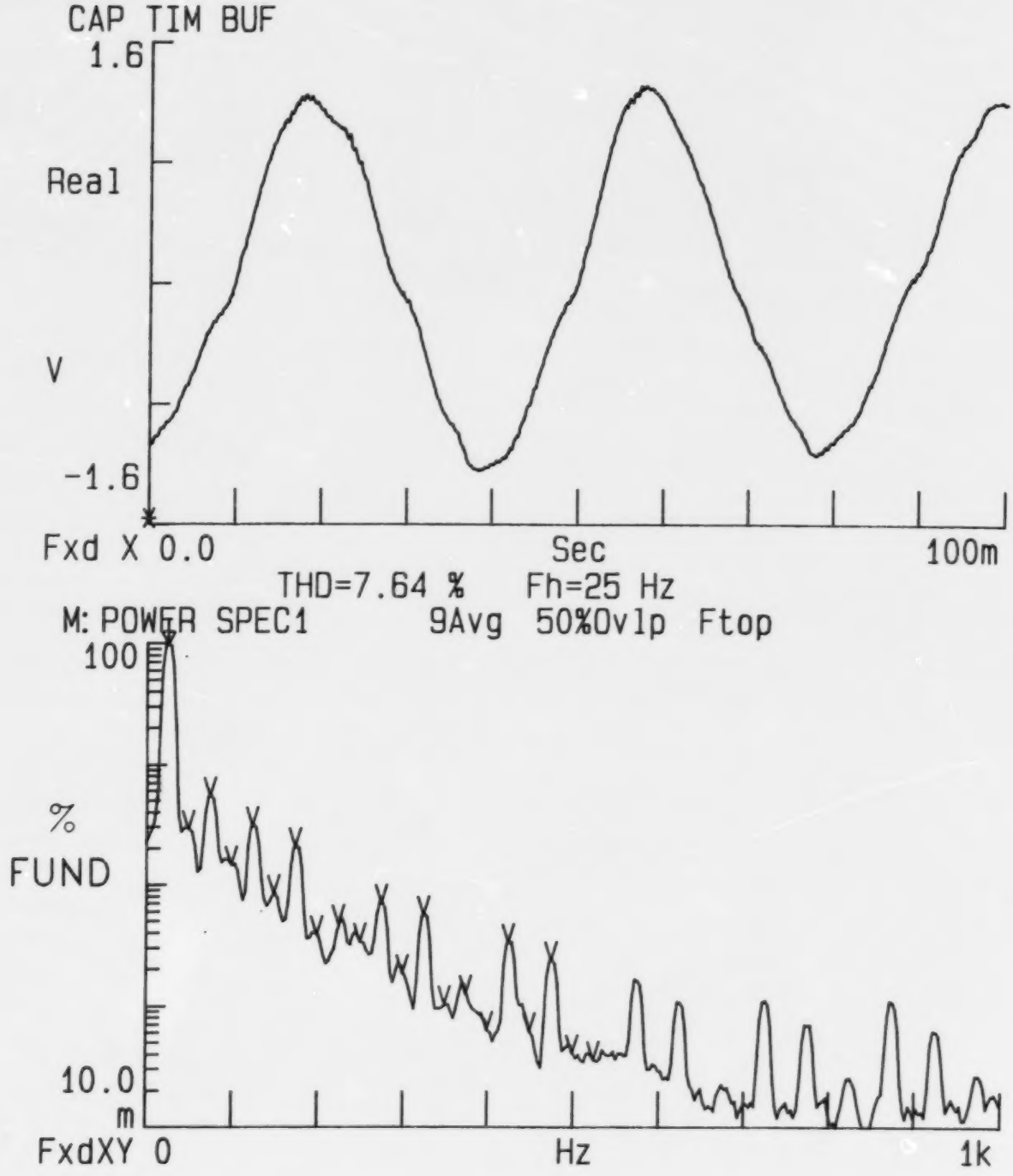


FIGURE 28 : Gage TS 25 Hz. M5 Feeder Current B Phase. Nov 26, 1987 09:52